

M104

The Science of Spiral Galaxies

How do they form, what are they made of, why do they look like they do?

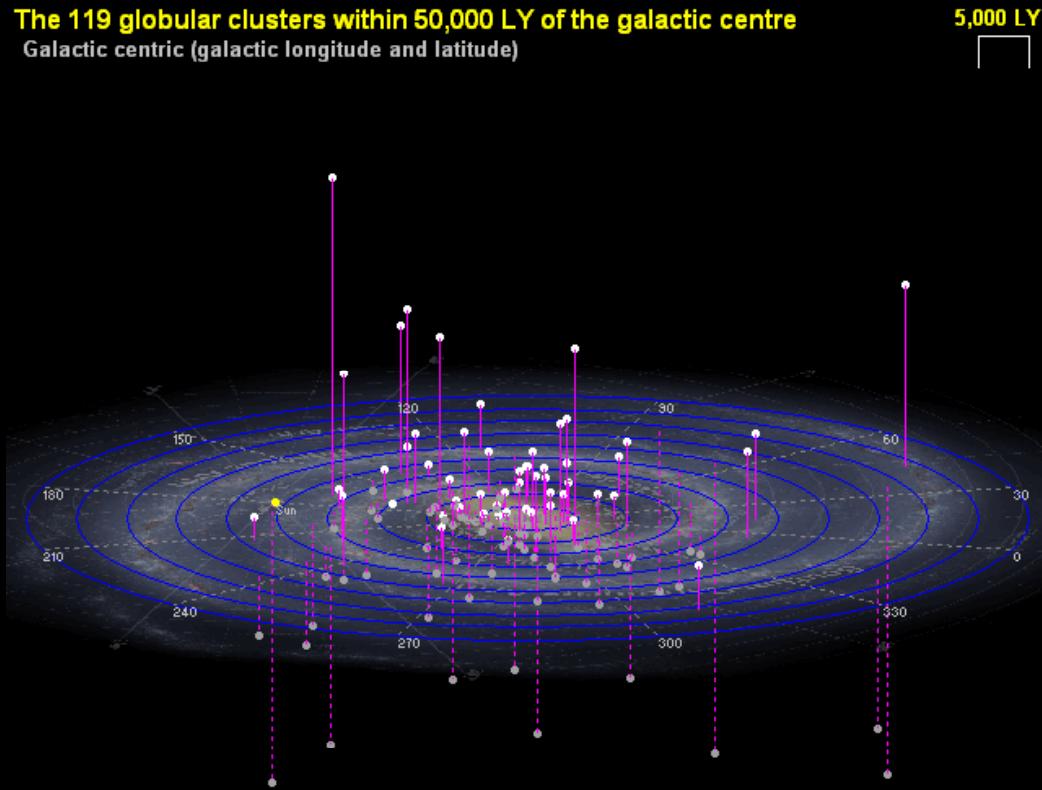
Simon Hanmer : OAWS *Understanding the Universe* #5, February 2017



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What is a “Galaxy” ?

The 119 globular clusters within 50,000 LY of the galactic centre
Galactic centric (galactic longitude and latitude)



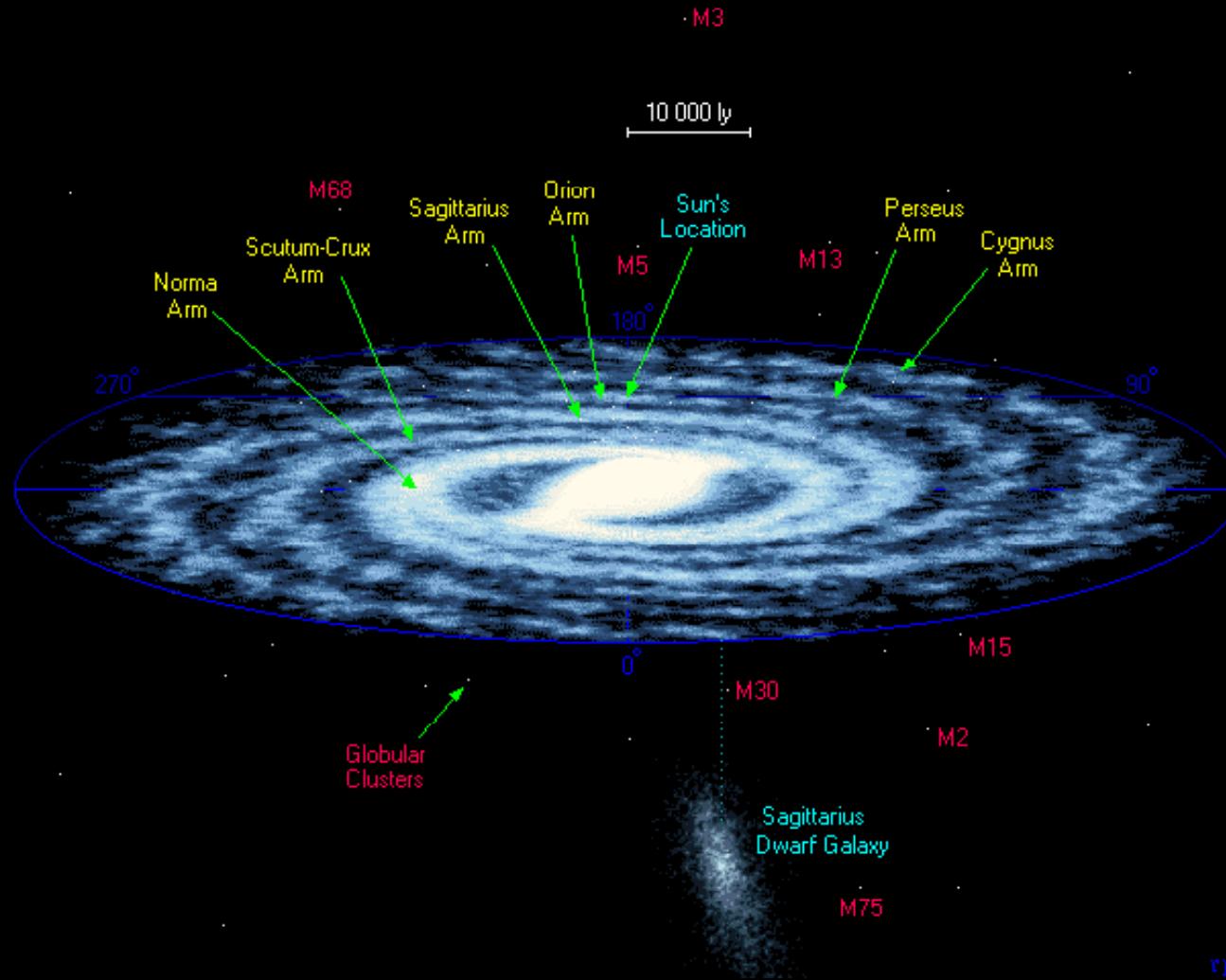
Data from William E. Harris, McMaster University
<http://www.physics.mcmaster.ca/Globular.html>

3D Diagram by Larry McNish

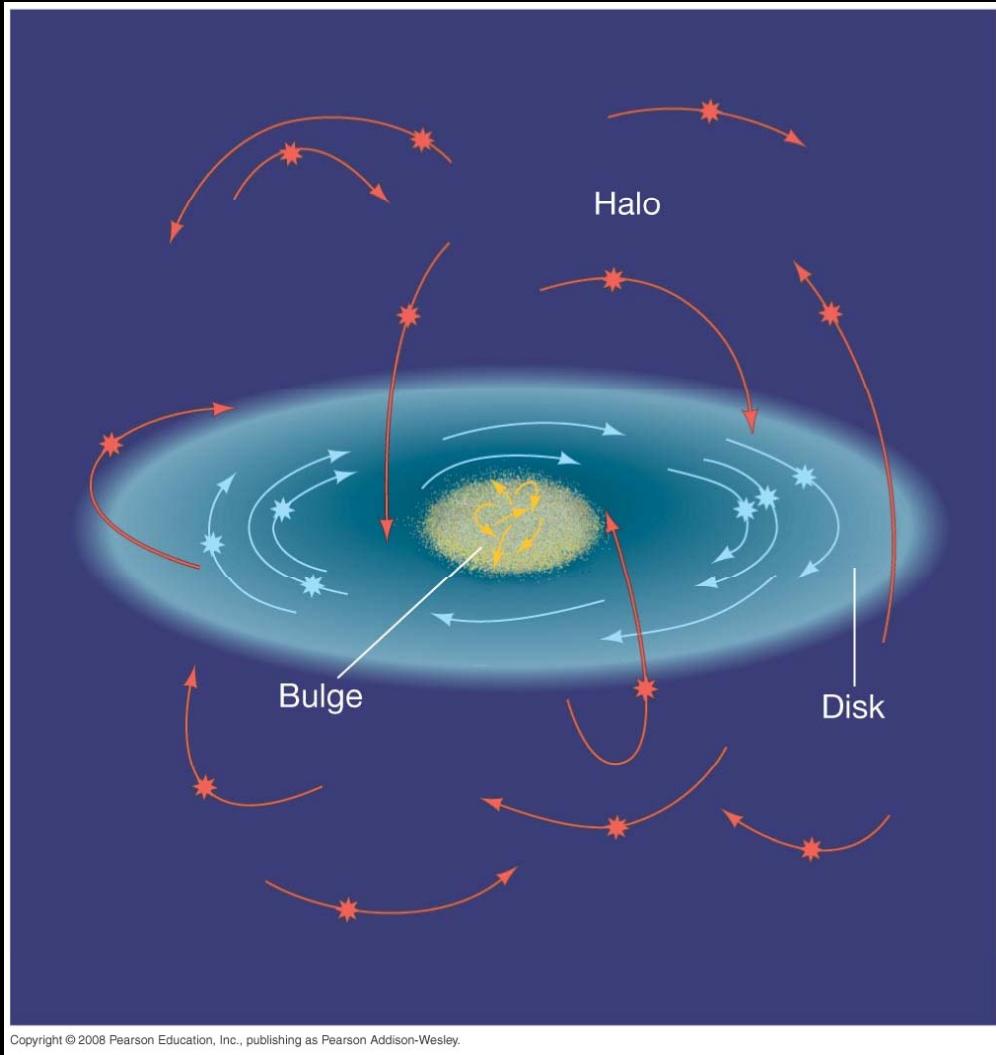
- 10^{11} stars
- Gas & dust ... or not !
- Disks or “spheres”
- Giants and dwarfs
- Arms (70%) ... or not ! *
- Symmetrical or “irregular” !
- Old !!
- + Globular Clusters ...



What is a “Galaxy” ?



What is a “Galaxy” ?



- 10^{11} stars
- Gas & dust ... or not !
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- Giants and dwarfs
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Galactic neighbourhood ... a “Supergroup”

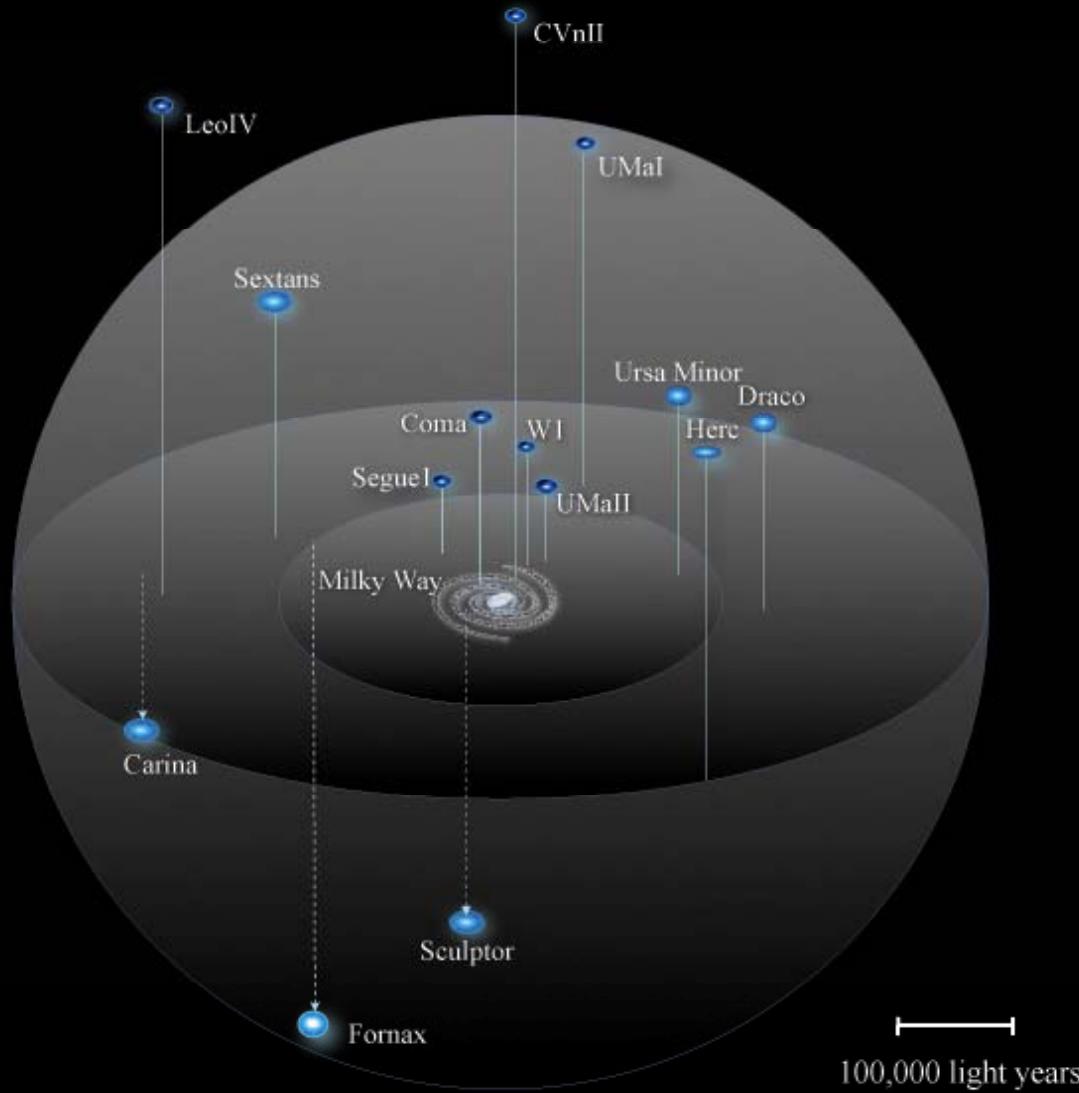
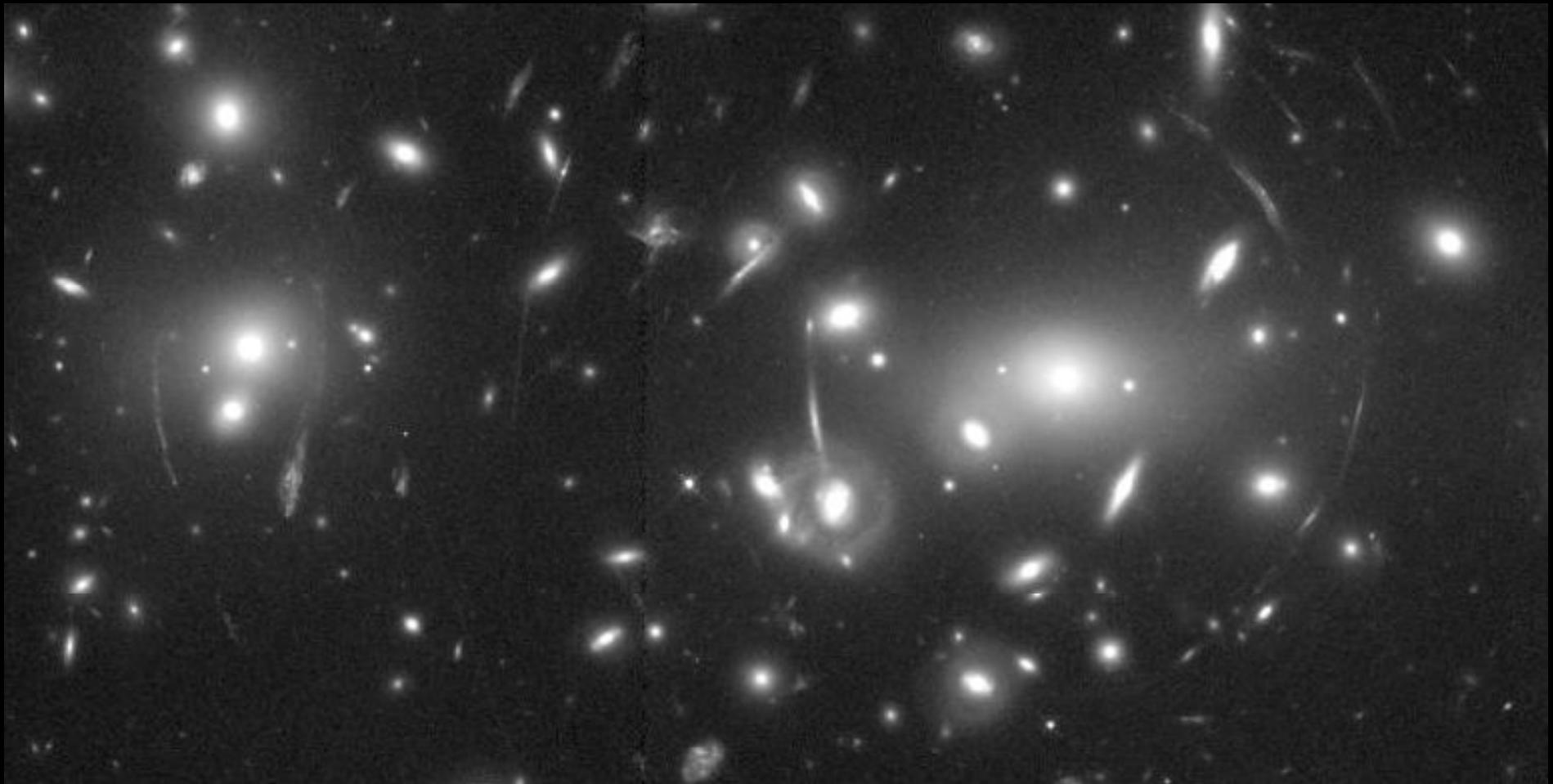


Image: J. Bullock/M. Geha/R. Powell



How many galaxies ? ... Abell 2218



How many galaxies ? ... Hubble Deep Field

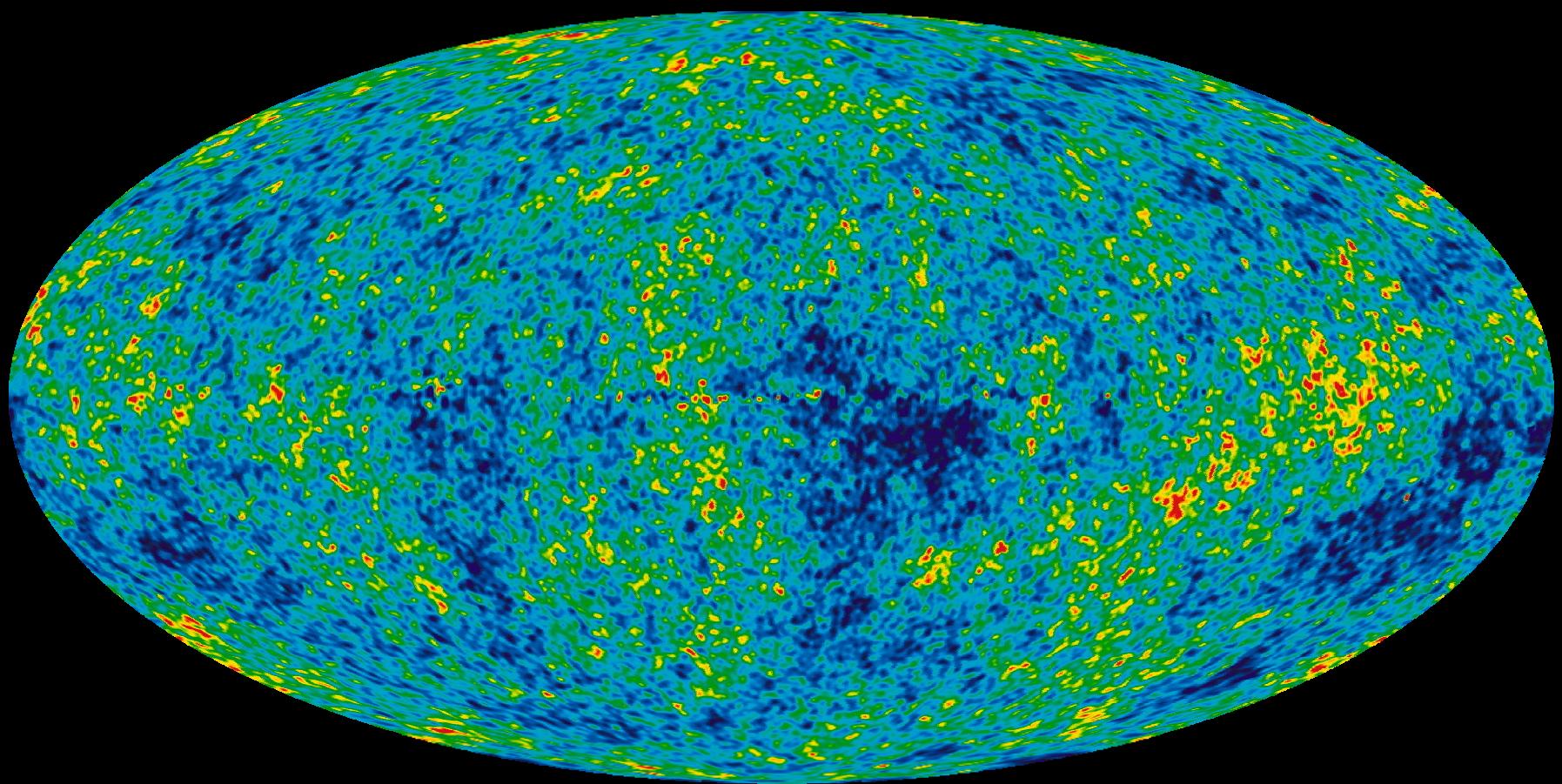


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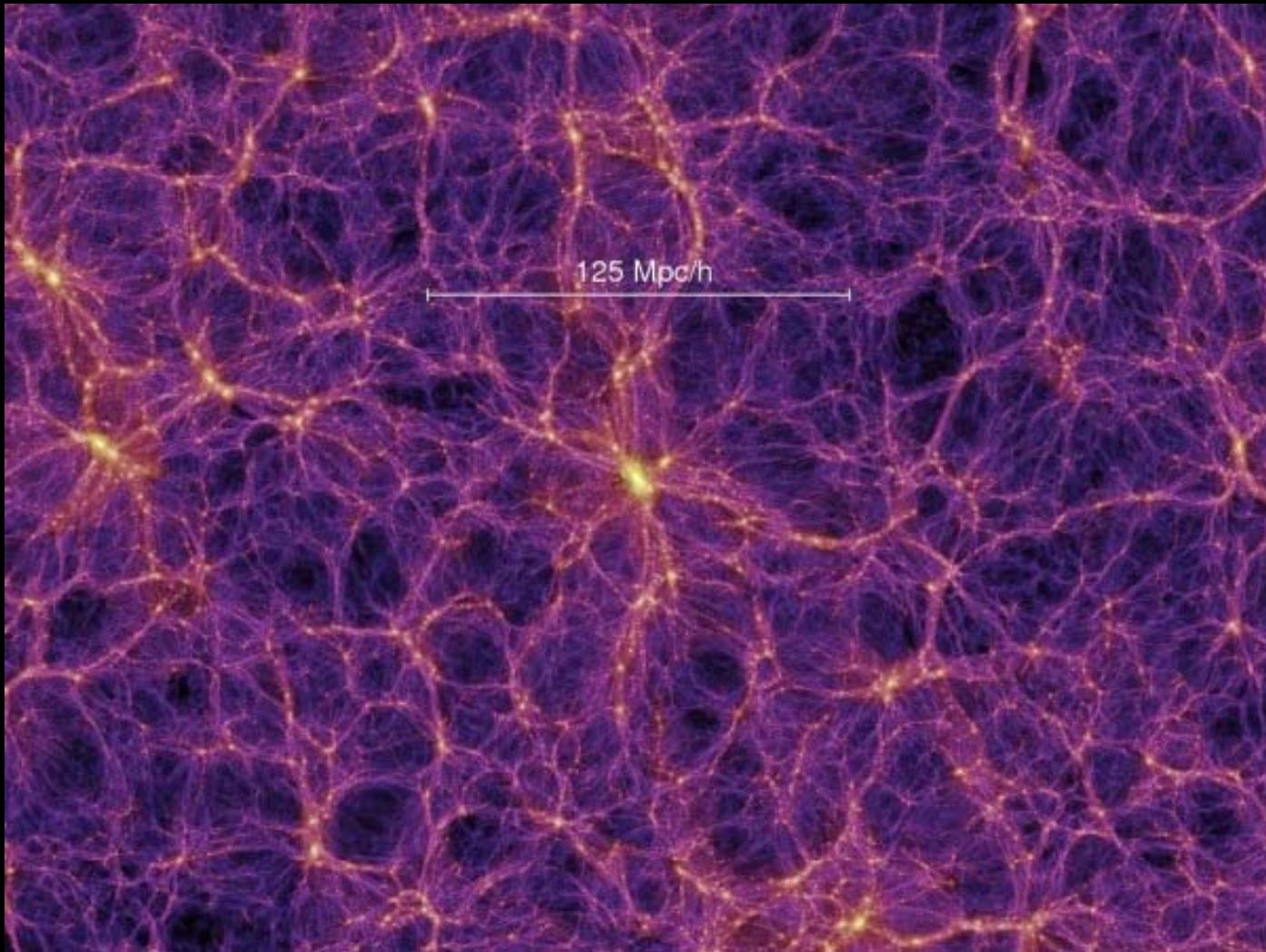
How did galaxies form ? ... microwave background

8/62



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How did galaxies form ? ... and where ?



How did galaxies form ? ... and where ?



How did galaxies form ? ... gravitational interaction

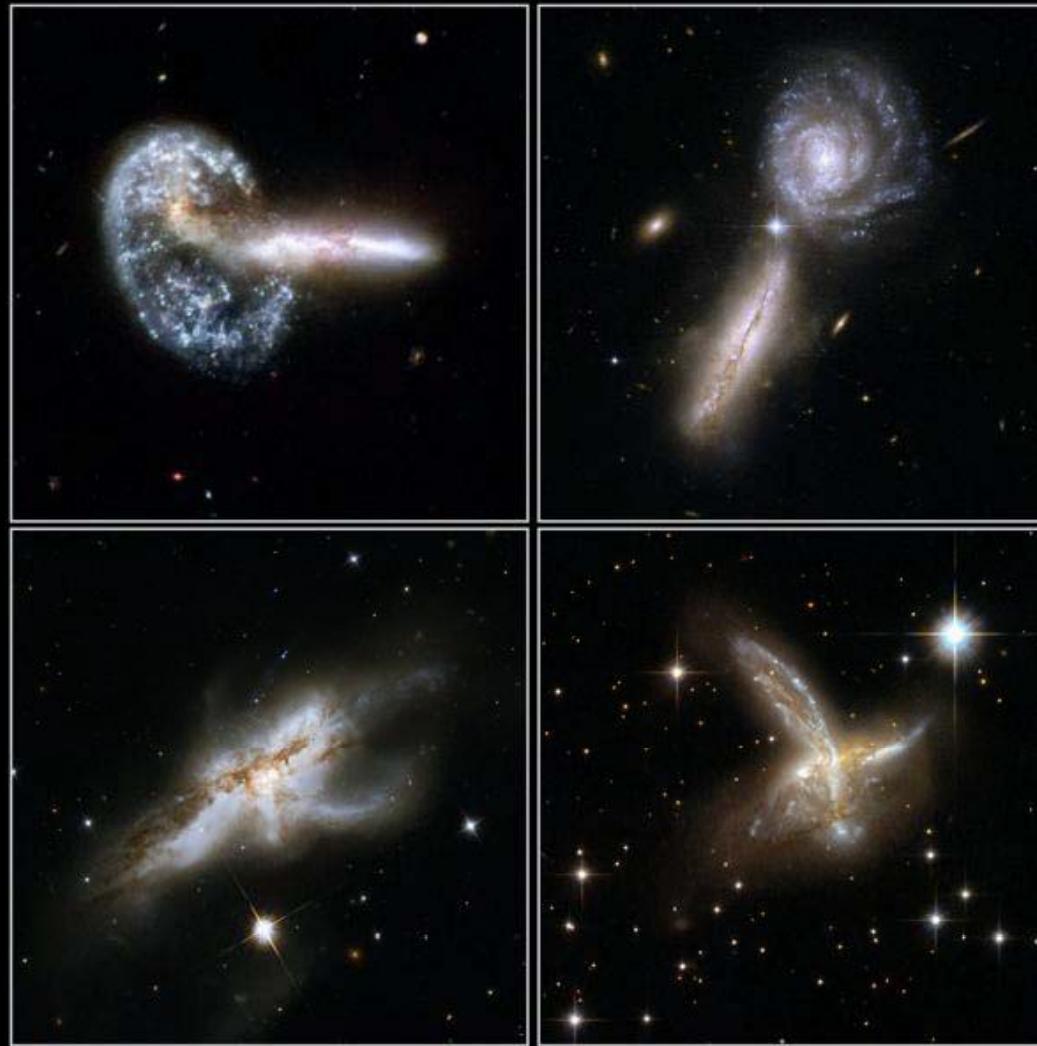
11/62

https://en.wikipedia.org/wiki/File:Andromeda_and_Milky_Way_collision.ogg



How did galaxies form ? ... gravitational interaction

12/62



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How did galaxies form ? ... Seyfert's Sextet



... in
Serpens



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How did galaxies form ? ... Stefan's Quintet



... in
Pegasus

NASA



How did galaxies form ? ... Magellenic Clouds



https://commons.wikimedia.org/wiki/File:Large_and_small_magellanic_cloud_from_new_zealand.jpg



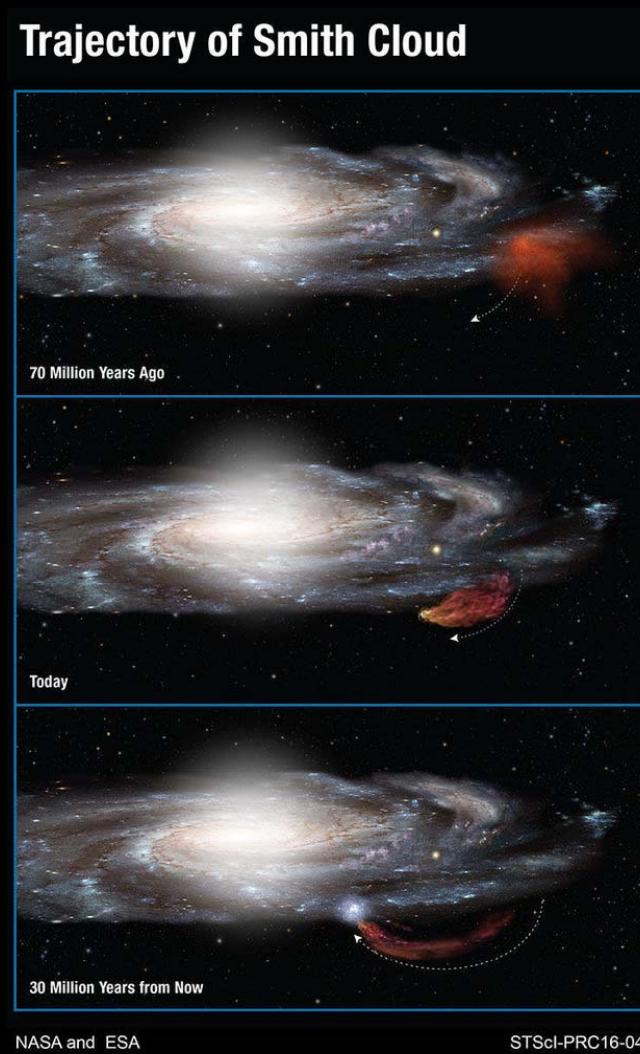
How did galaxies form ? ... Large Magellenic Cloud

16/62



 *Public Domain, <https://commons.wikimedia.org/w/index.php?curid=57110>*

How did galaxies form ? ... Smith Cloud



How did galaxies form ? ... M31/32/110

* Dark matter accelerator ?



* Early core-bulge, later disk ?

Problem : many distant galaxies are already very large ! *

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What do galaxies look like ? ... 70% are spirals

19/62

Open



Tight

SBa

SBb

SBc

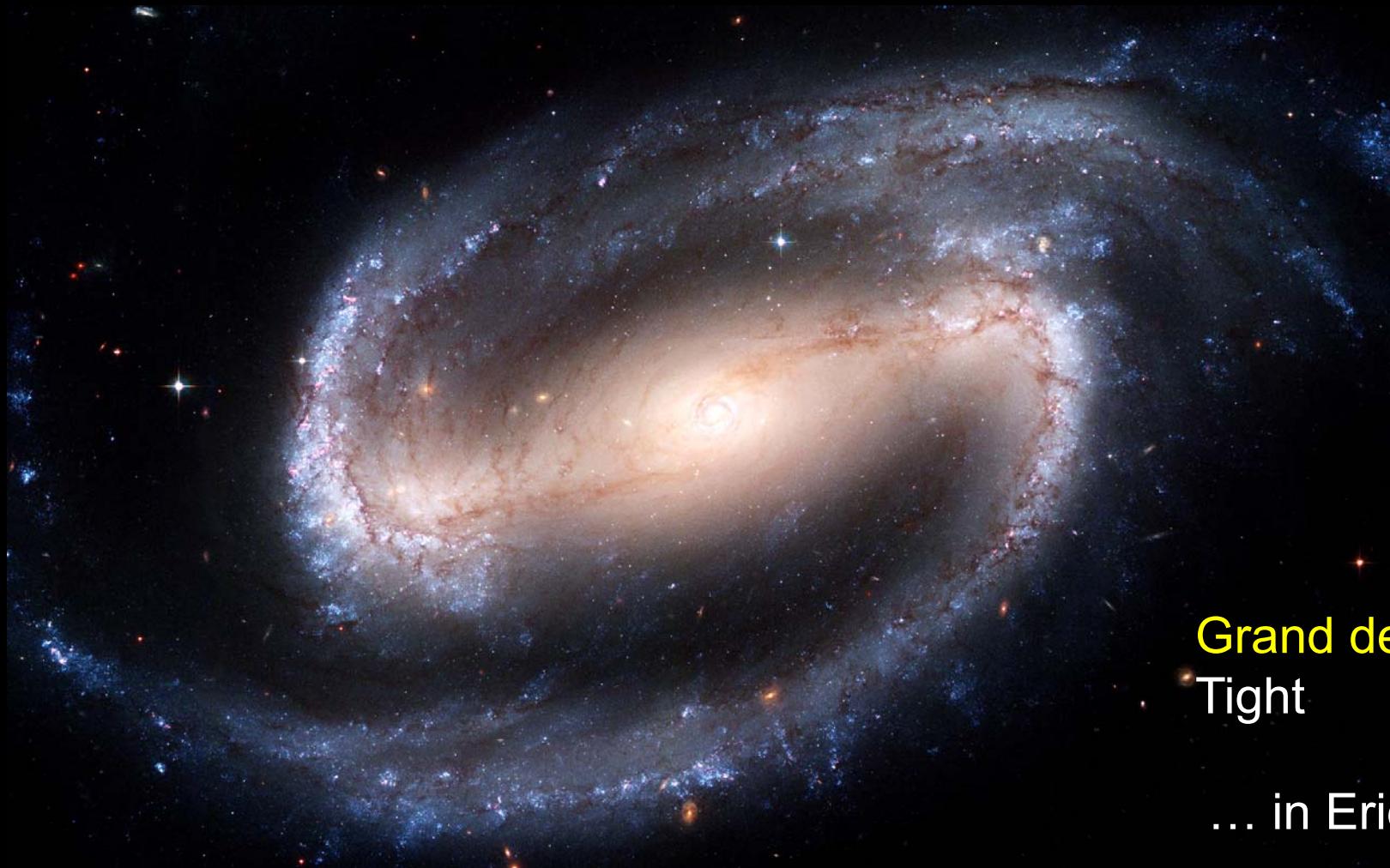
Perception that the stars are located only in the spiral arms is deceptive ... *the arms are only relatively dense*

Laurine Moreau / Space Facts

Laurine Moreau/Space Facts



What do galaxies look like ? ... NGC 1300 : barred spiral



Grand design ...
Tight

... in Eridanus

NASA



What do galaxies look like ? ... NGC 1365 : barred spiral



Grand design ...
Open

... in Fornax

Martin Pugh



What do galaxies look like ? ... M51 “Whirlpool” 22/62



- Iconic face-on multiarm spiral ...
- ... but not pristine !
- *We'll come back to this ...*



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What do galaxies look like ? ... M33 “Triangulum”^{23/62}



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What do galaxies look like ? ... M100 “Pinwheel” 24/62



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What do galaxies look like ? ... Spiral galaxies

25/62

- Grand design : 10%
- Multiple arm : 60%
- Flocculent : 30%



What do galaxies look like ? ... M63 “Sunflower” 26/62



Flocculent ...

> Gas ...
Weak spiral in
IR

NASA



What do galaxies look like ? ... M104 Sombrero 27/62



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What do galaxies look like ? ... NGC 4565 : edge-on

28/62



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What do galaxies look like ? ... NGC 891 : edge-on

29/62



NASA



What do galaxies look like ? ... NGC 5866 : needle-like



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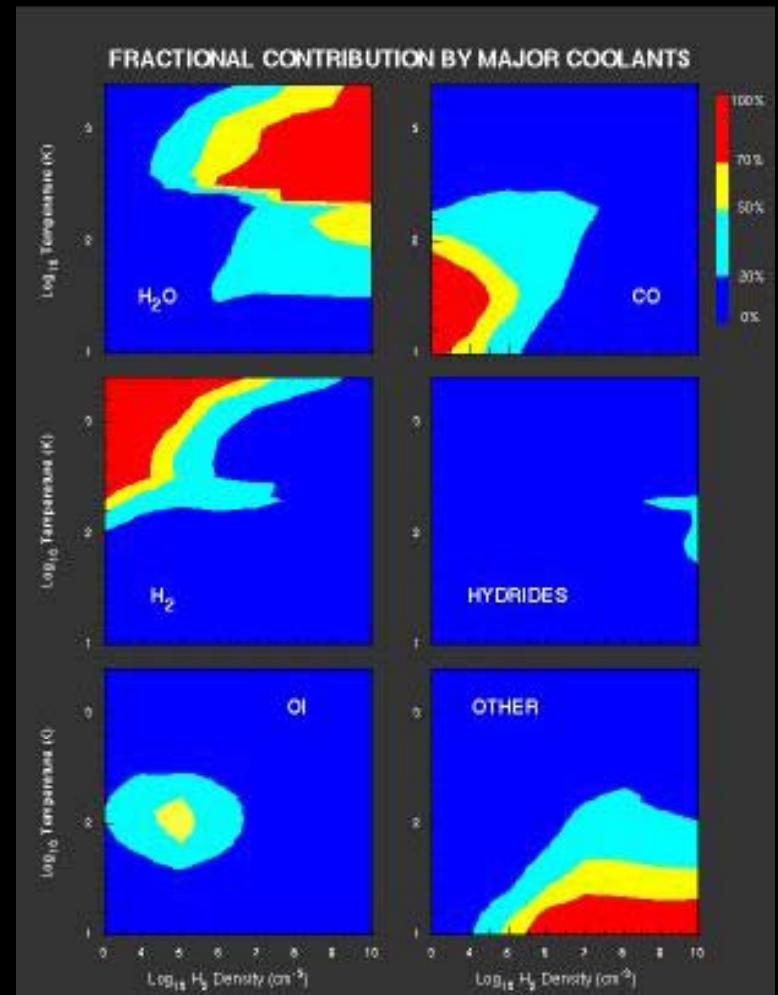
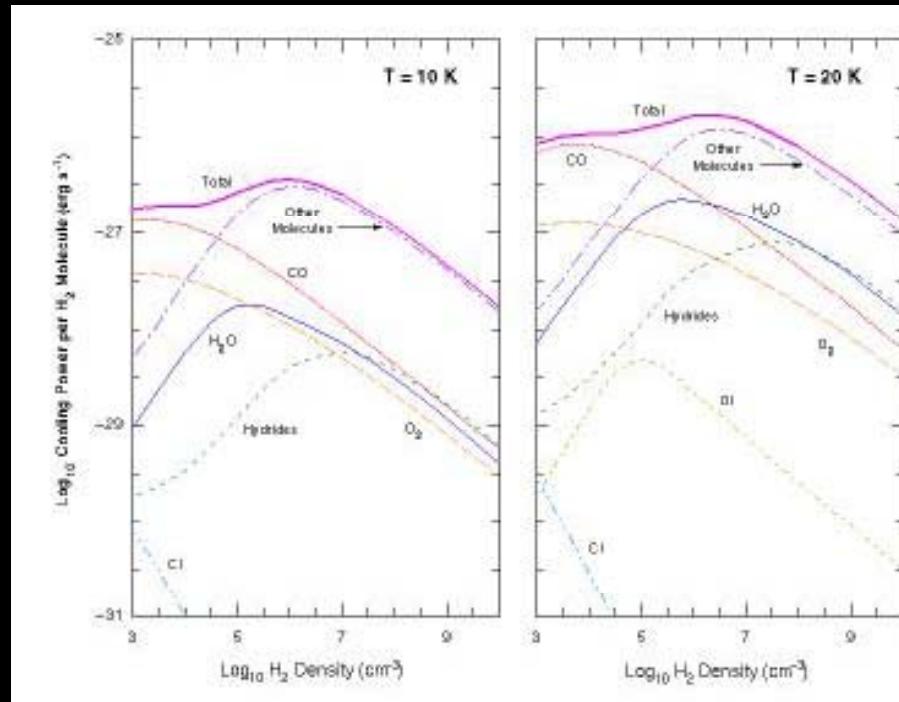


Galactic evolution ? ... coolants required ! : $f(\rho, T)$

31/62

Jeans instability ...

Collapse = $f(\rho)$ and $f(T)$



Kinetic E \Rightarrow potential E \Rightarrow photon emission + escape \Rightarrow *cooling*

<https://www.cfa.harvard.edu/swas/science1.html>



What do galaxies look like ? ... M 60 : elliptical

32/62



Spherical to elliptical

Random (radial) orbits
cf. *globular clusters*

Old, low-mass red stars

Gas ... but low star formation rates ($f(T)$)

Centres of galaxy clusters (*accretion*)

NASA



What do galaxies look like ? ... IC 2006 : elliptical

33/62



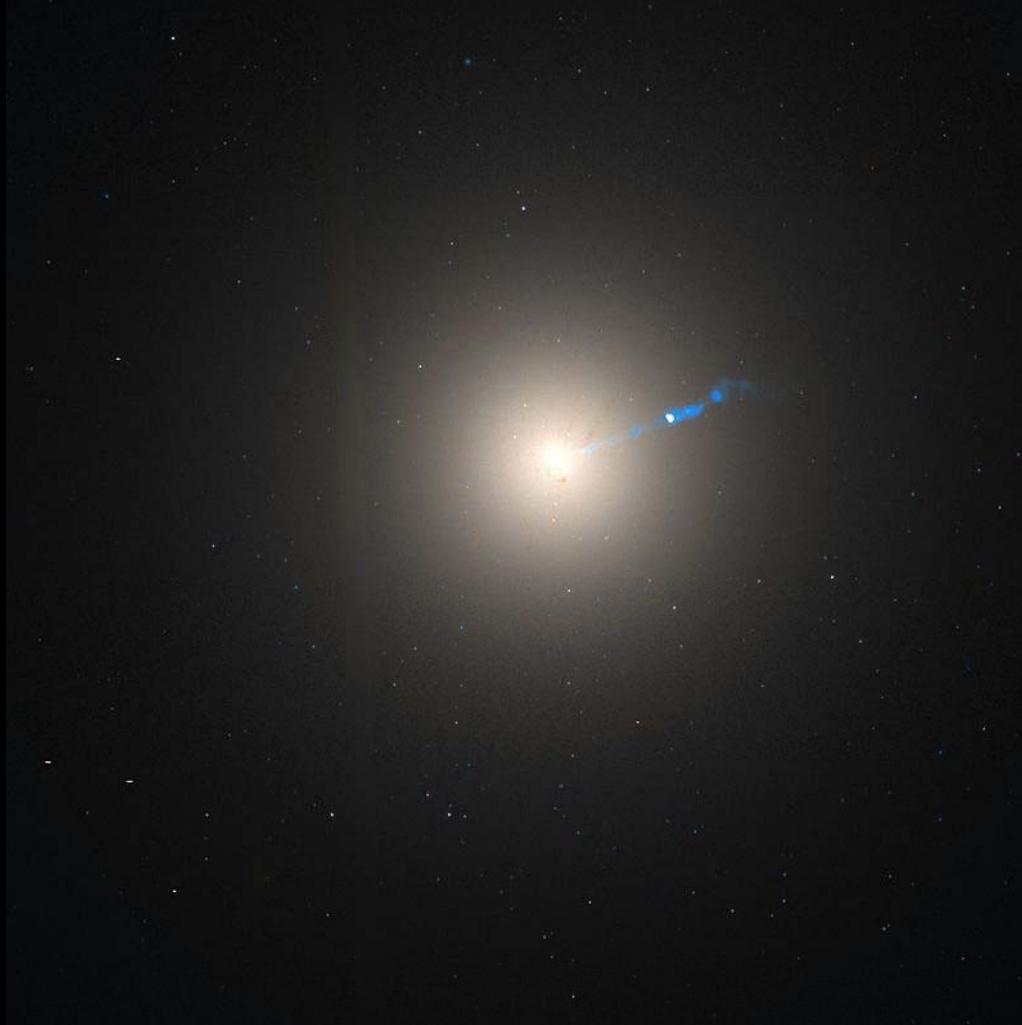
... in Eridanus



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What do galaxies look like ? ... M 87 : elliptical

34/62



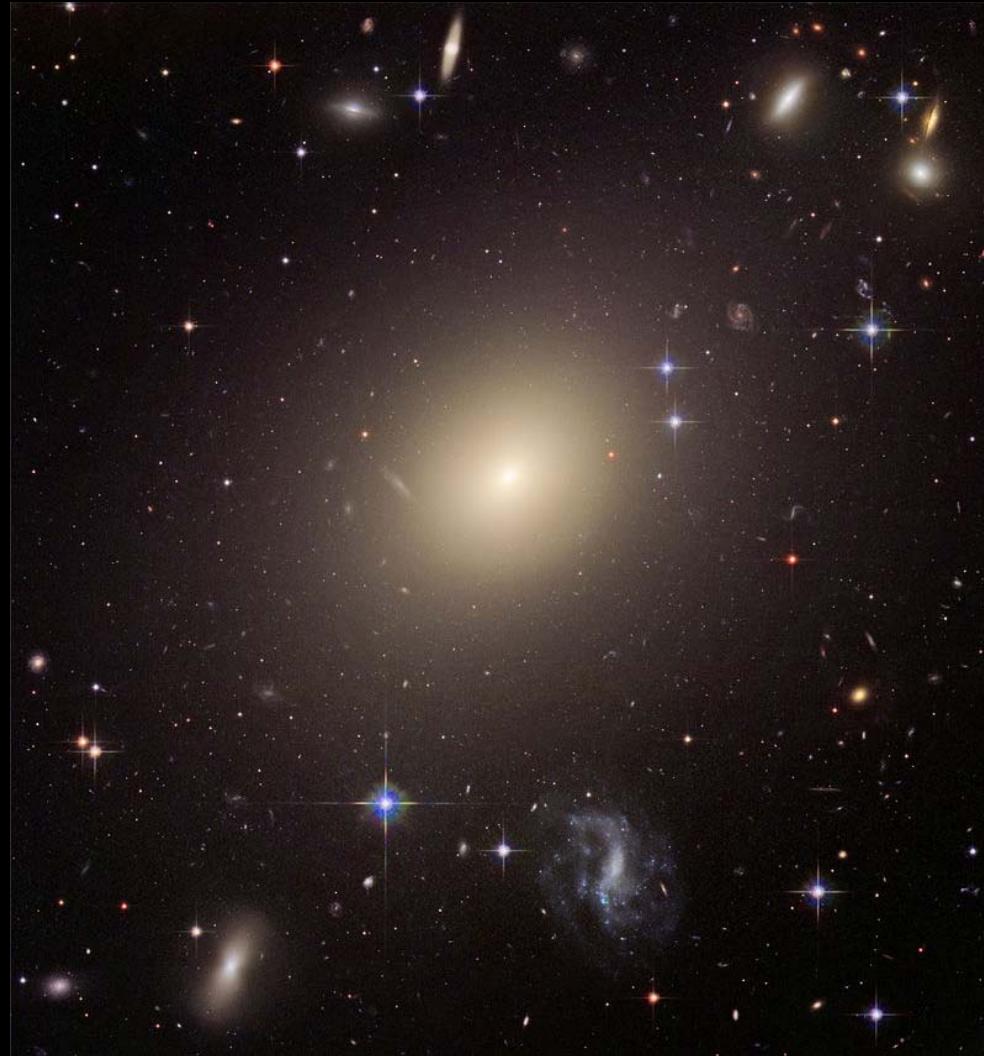
... in Virgo Cluster

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What do galaxies look like ? ... Abell : elliptical

35/62



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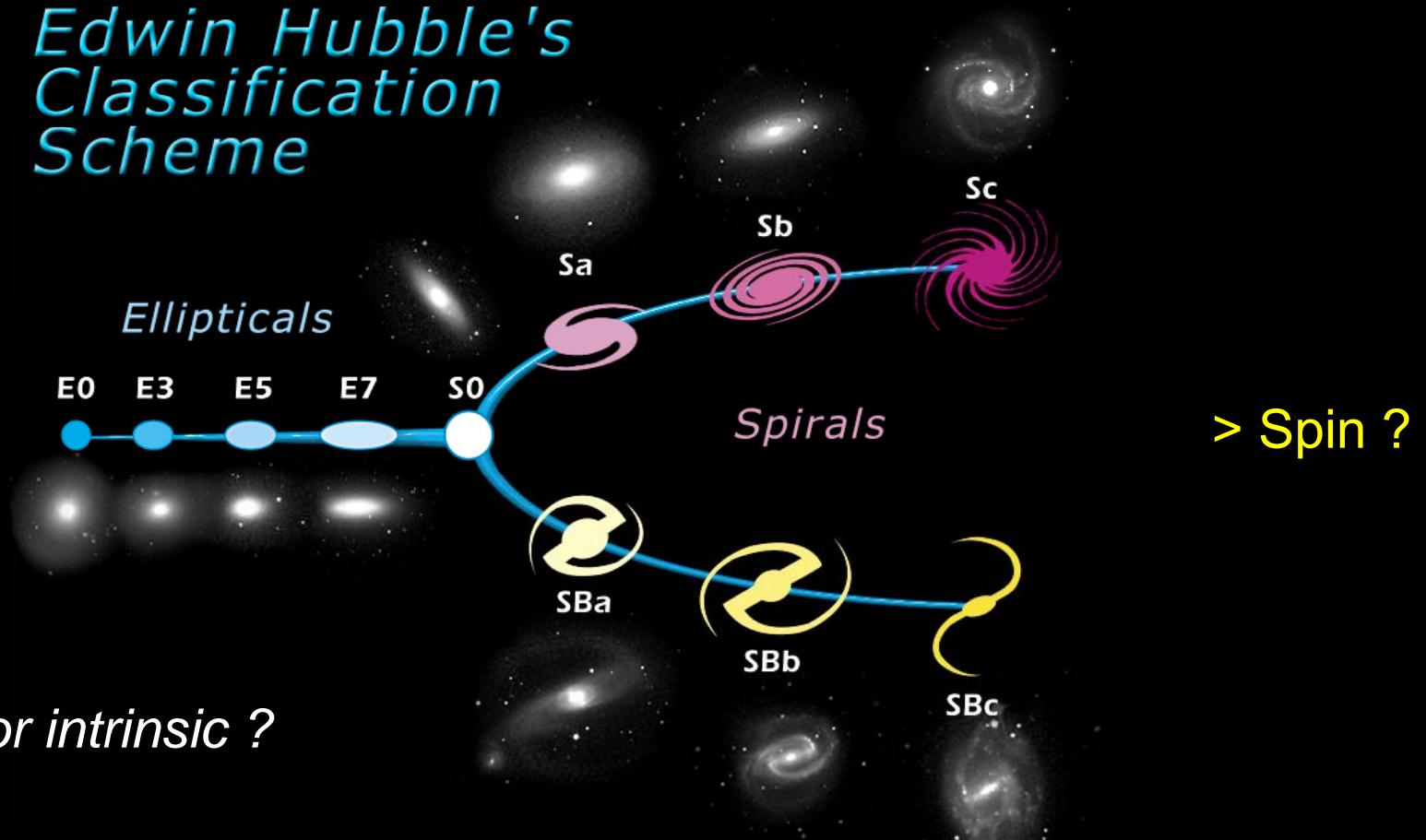
Galactic evolution ? ... wrong ! – still wrong ?

*Edwin Hubble's
Classification
Scheme*

< Spin ?
or
Merger ?

Sequential or intrinsic ?

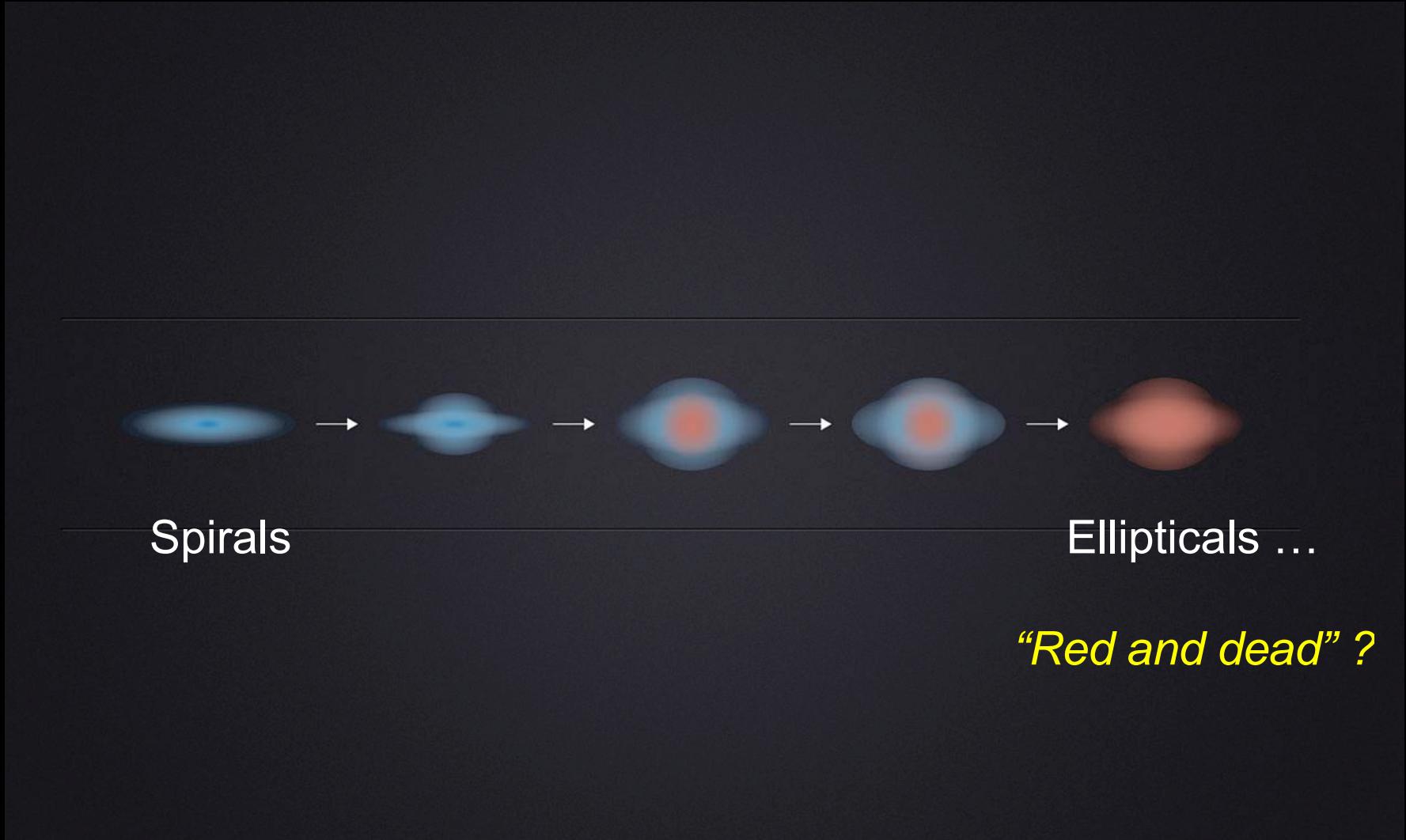
Density ?



https://en.wikipedia.org/wiki/Hubble_sequence



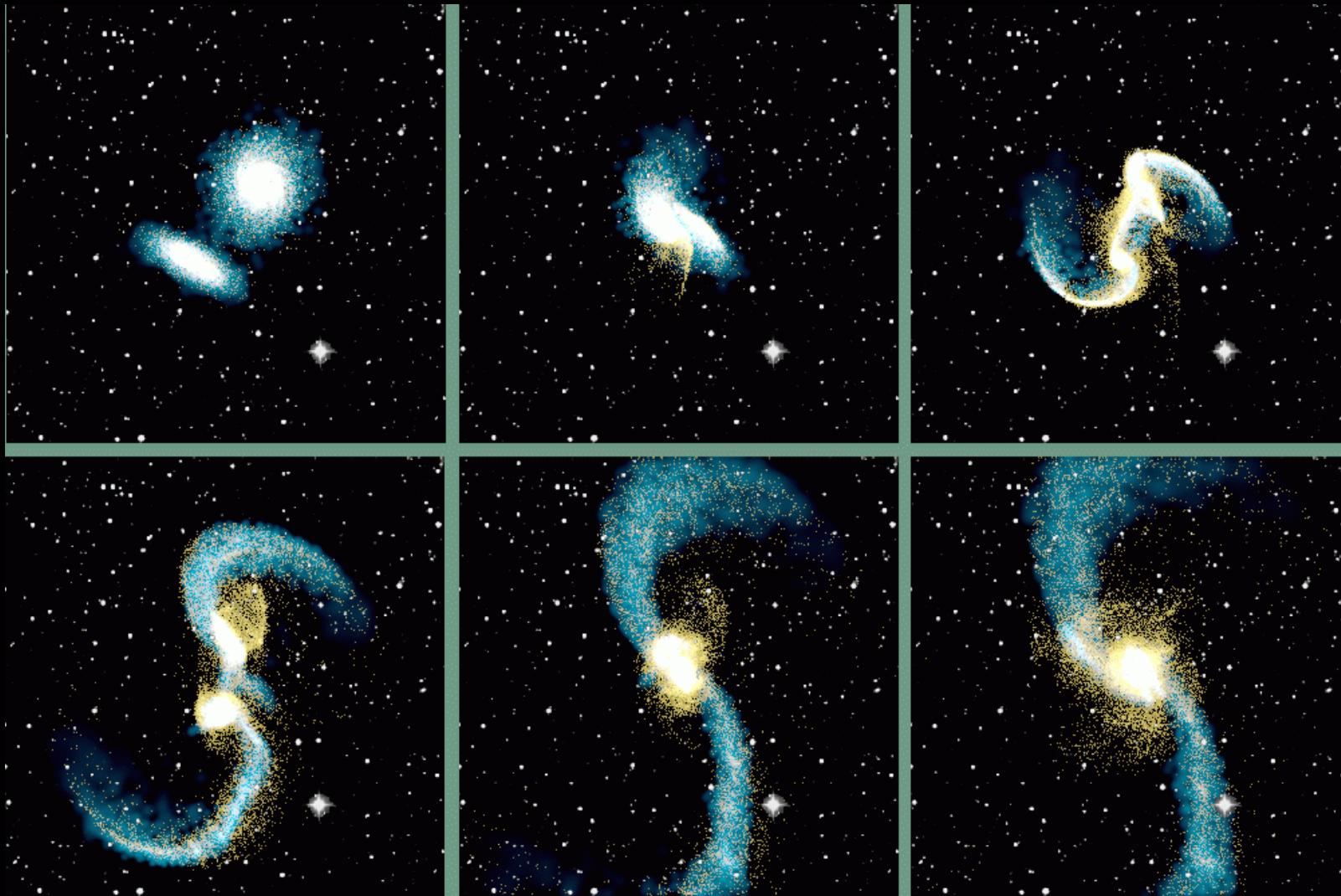
Galactic evolution ? ... thermal sequence ?



<http://www.space.com/29123-ancient-galaxies-die-inside-out.html>



What do galaxies look like ? ... Irregular



Irregular galaxies ... NGC 4038/9 “Antennae” model

39/62



http://www.ifa.hawaii.edu/users/barnes/research/interaction_models/index.html



Irregular galaxies ... NGC 4038/9 “Antennae”

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... in Corvus

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Irregular galaxies ... NGC 4676 “Mice”

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... in Coma Berenices

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Irregular galaxies ... M51 “Whirlpool”



NASA



The Science of Spiral Galaxies

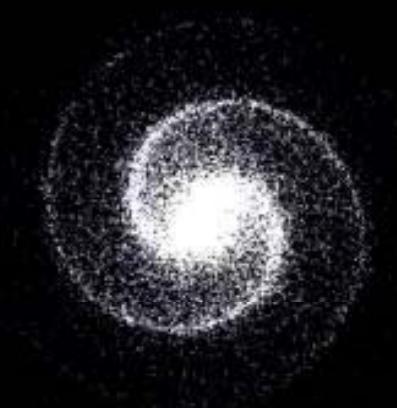
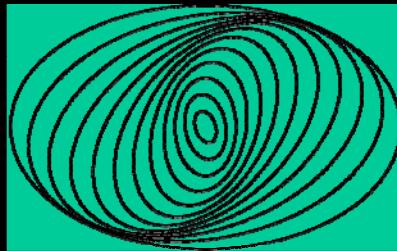


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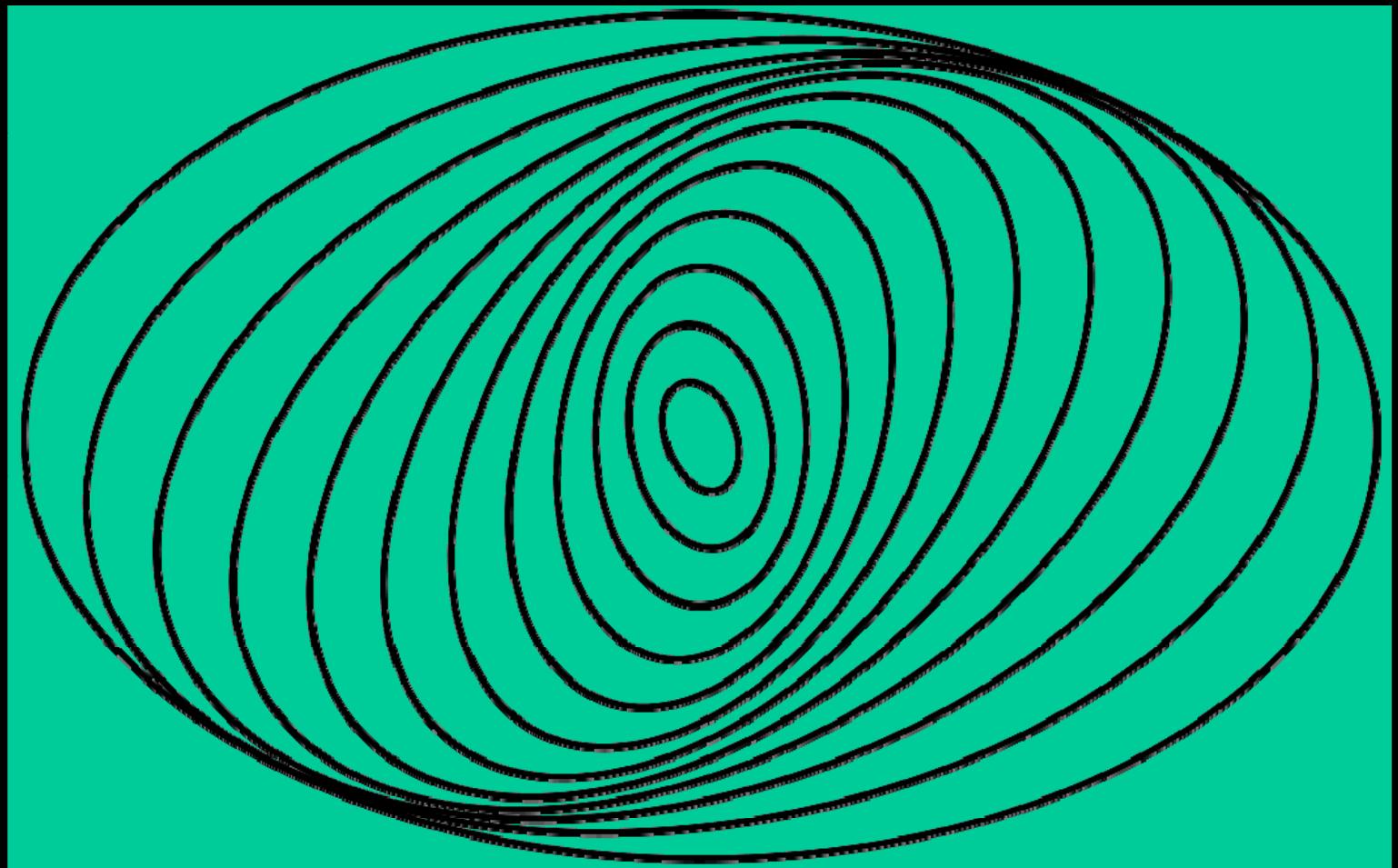
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What is a spiral galaxy ? ... geometrical “pond” analogue

Note the bar ...



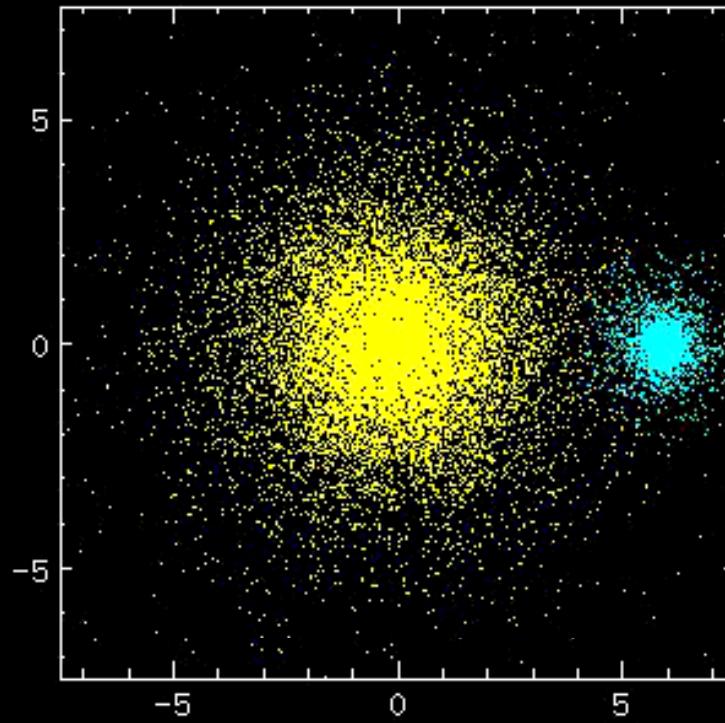
*Disturbances ...
For example ...*



https://en.wikipedia.org/wiki/Density_wave_theory



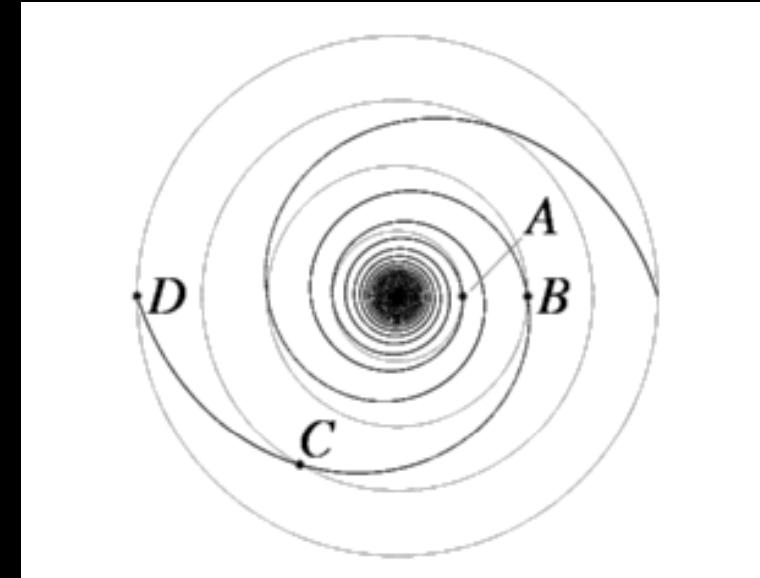
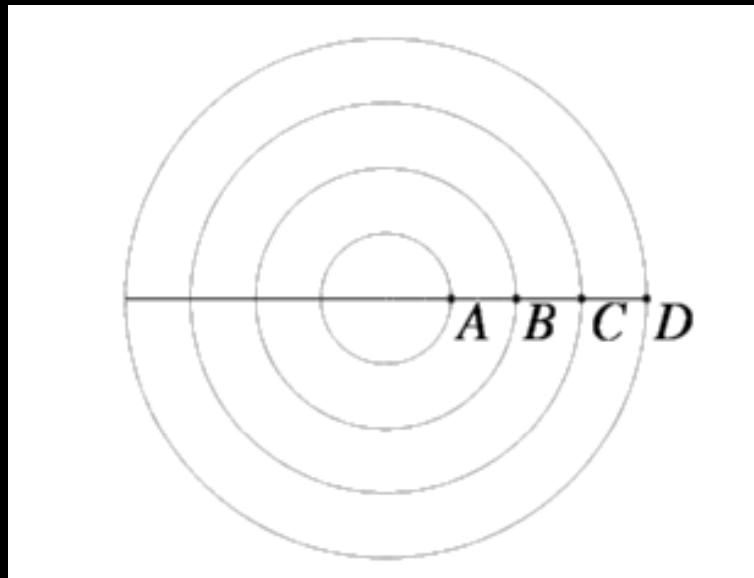
How do spirals form ? ... interaction model



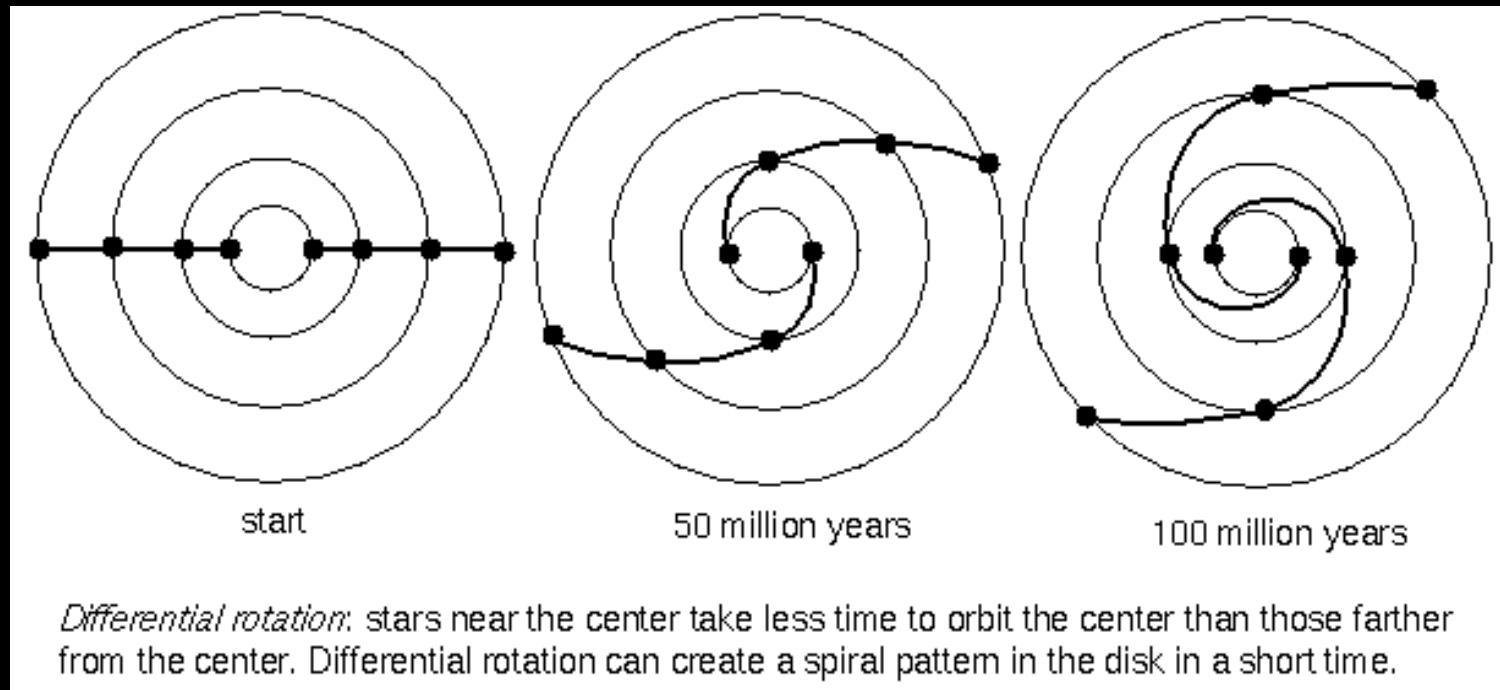
<http://burro.cwru.edu/academics/Astr222/Galaxies/Spiral/spiral.html>



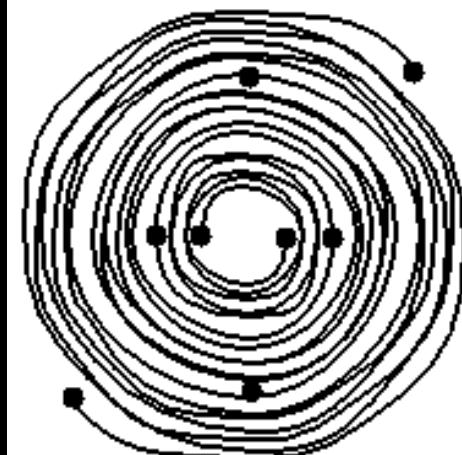
What's the problem ? ... winding! i.e. kinematics 46/62



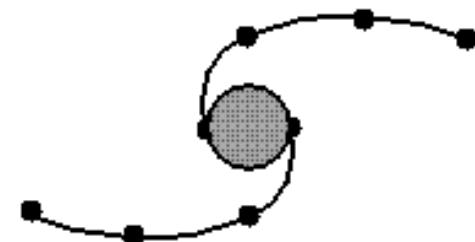
What's the problem ? ... winding !



What's the problem ? ... winding !

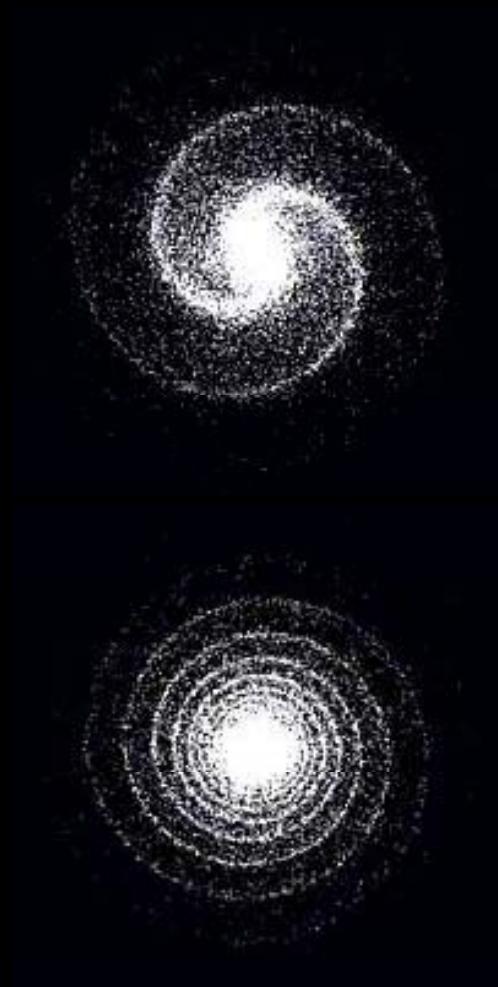


Prediction: 500 million years

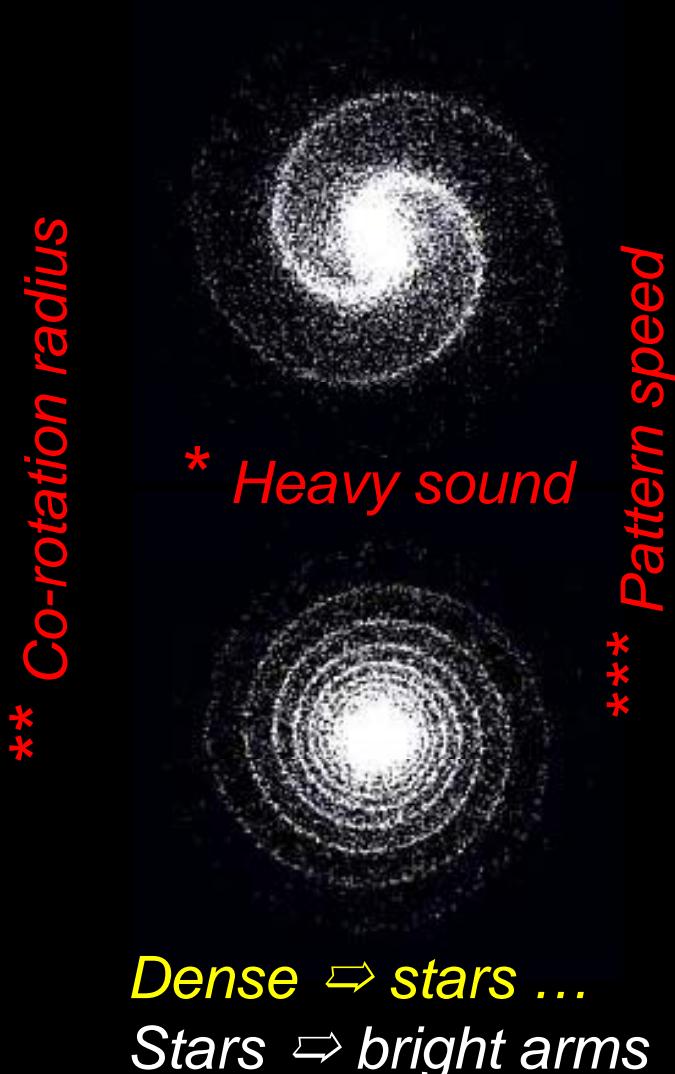


Observation: 15,000 million years

The “winding problem”: because of differential rotation, the spiral arms should be so wound up after a short time that the spiral structure has disappeared. Observation contradicts the prediction. What keeps the spirals loose?



Why don't spiral galaxies wind-up ? ... dynamics 49/62



Spirals : gravitational interactions between stars and gas in shearing, rotating disk

Old ideas : “garden sprinkler”, detonation wave, and magnetic field theories – (*material points*)

Density waves * (relative density 10-20% + disturbances) : stars overtake “wave” in inner galaxy, and vice versa** in outer galaxy ... compacted dust lanes predicted on inside of *trailing* spiral arms ***

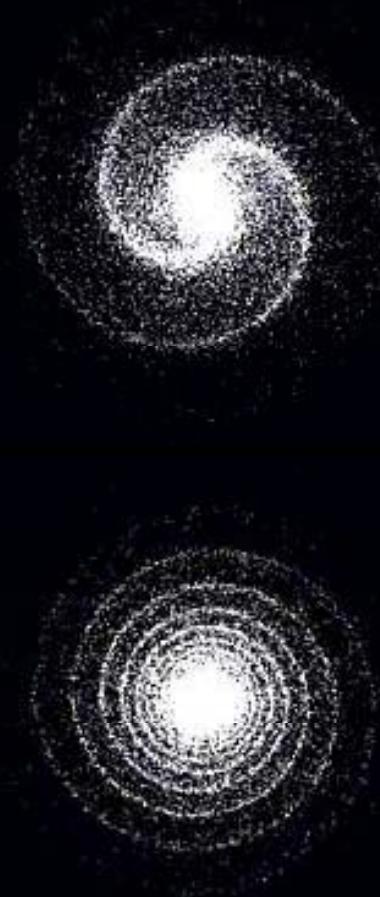
However ... inner wave migrates in and outer wave migrates out – and spiral arm dampens and dies ☺ See : <http://ned.caltech.edu/level5/ESSAYS/Carlberg/Carlberg.html>

<http://casa.colorado.edu/~danforth/science/spiral/>



Why don't spiral galaxies wind-up ?

https://en.wikipedia.org/wiki/Density_wave_theory



So : a little theory on why arms “*trail*” 😢😢😢

See :

<http://ned.caltech.edu/level5/ESSAYS/Carlberg/carlberg.html>

So many stars means galaxies are self gravitating systems that want to increase their gravitational energy

∴ in inner galaxy stars migrate inward

Migration \hookrightarrow < angular momentum – allowed by opposed torque as inner stars are pulled back by outer stars ... **further back** in the same arm

Result : gravitational energy of inner stars increases at expense of outer stars in *trailing* arms



Why don't spiral galaxies wind-up ?



Swing amplification : 😢😢😢

Same gravitational exchange that dampens trailing arms leads ***leading*** arms migrate out and ***amplify fast*** !

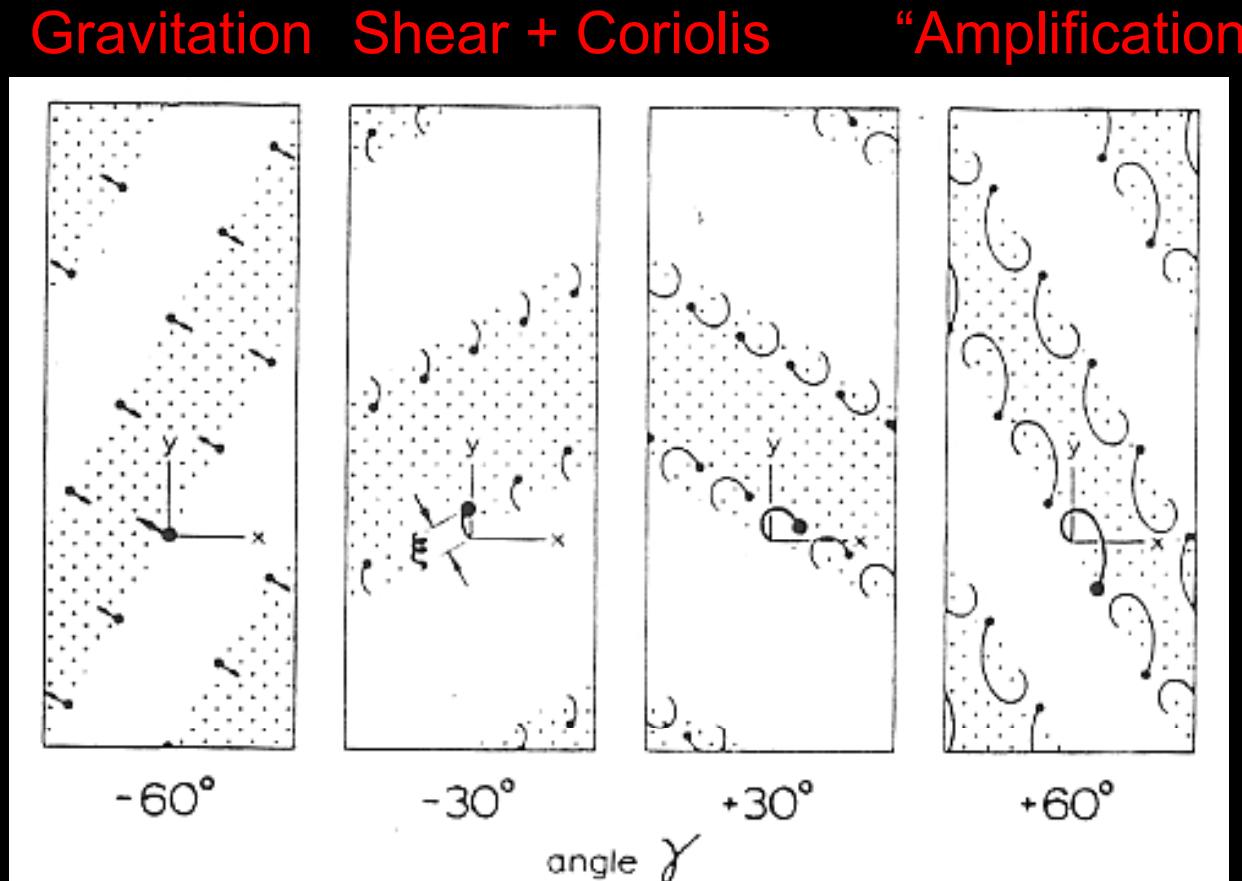
Amplification of “***perturbators***” pumped-up by ***resonances*** related to ***en masse*** stellar motions (***radial oscillations***)

Disk rotation (***shearing***) bends arm backwards ...

... behaves as a trailing arm 😊



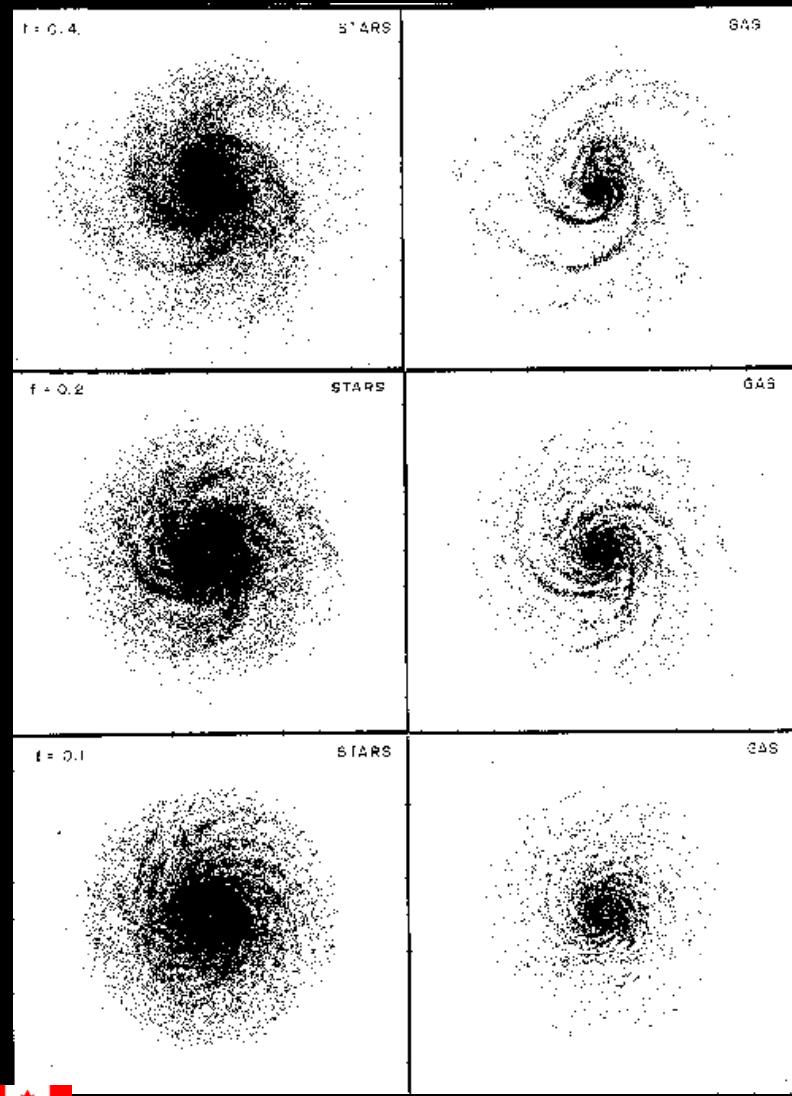
Swing amplification ... shear and self-gravity



Swing
amplification
per se favours
Grand Design
2-arm spiral
galaxies ... so
*what about
the others ?*



Linear modelling spiral galaxies ...



Model :

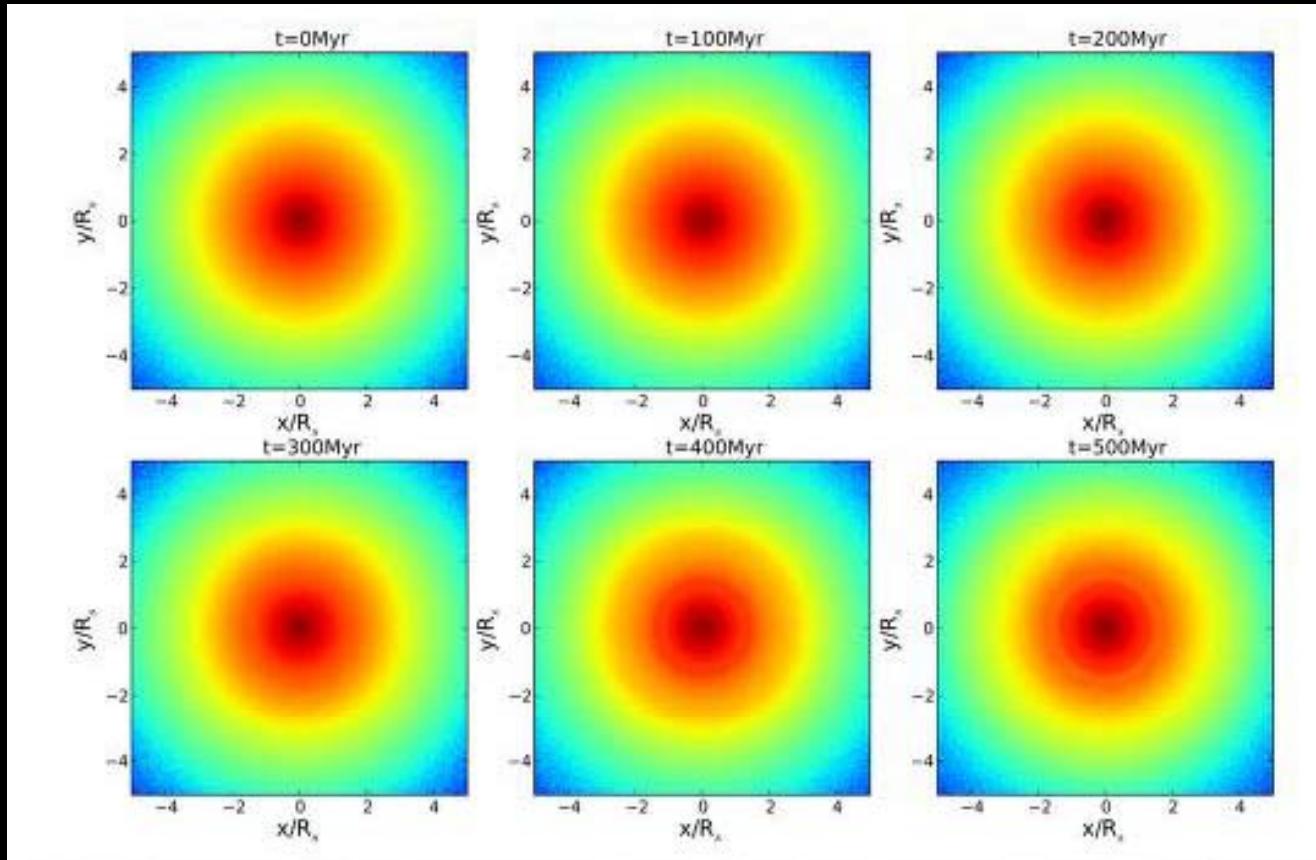
30,000 superstars & 10,000 super gas clouds

Increasing Halo/Disk mass ratio

However ... spiral structure is transient
and fluctuating – but enduring ☺



How do spirals form and self maintain ?



Linear (*transient spirals*) vs **non-linear** numerical modelling

Spirals originate from density **inhomogeneity** (*molecular clouds*)

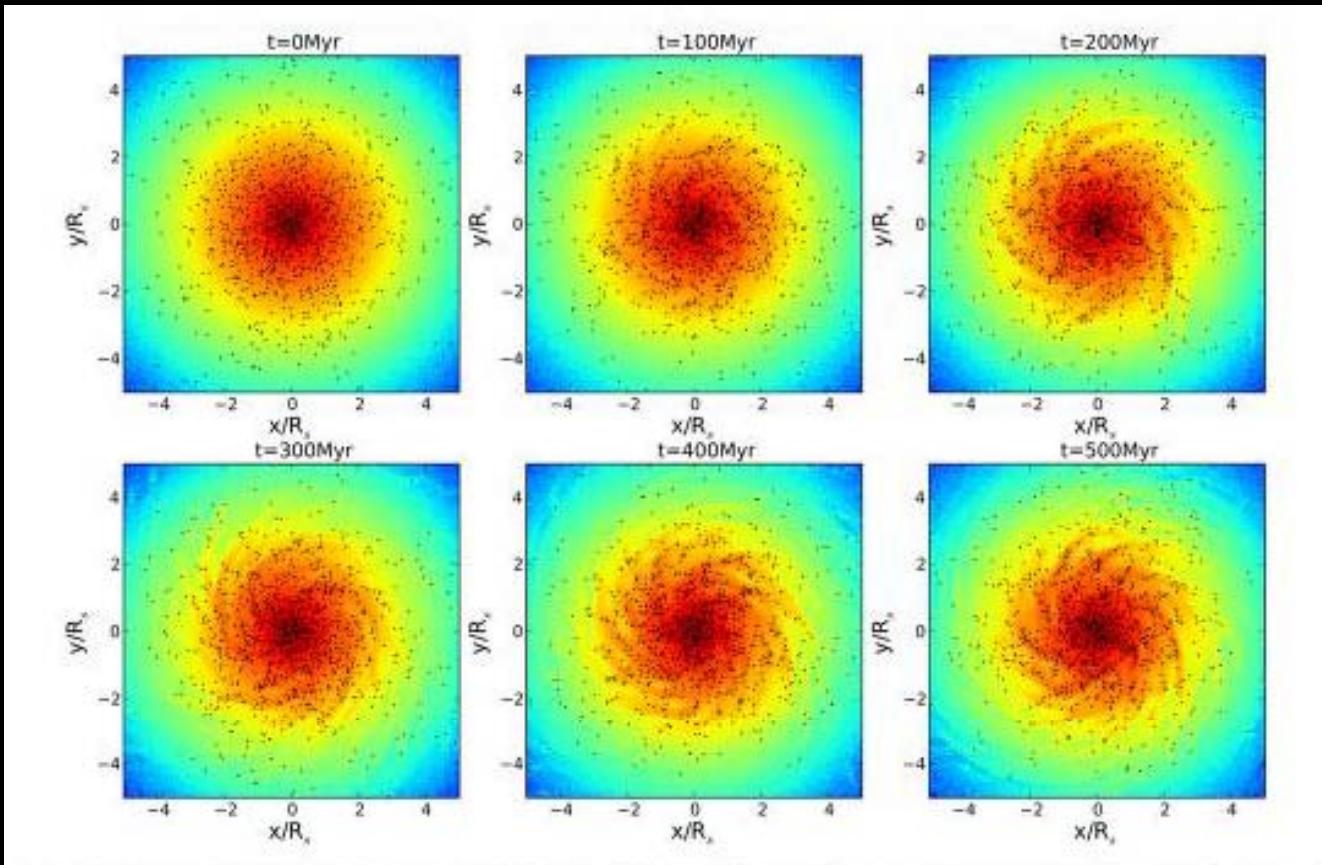
Swing amplification ... of pre-existing leading “*wakelets*”

Model stellar disk stability test

Onghia, Vogelsberger and Hernquist, arXiv, 2013



How do spirals form ?



Shear vs self-gravity = equilibrium
Local vs global pattern

Onghia, Vogelsberger and Hernquist, arXiv, 2013

Model stellar disk with 1000 co-rotating “soft” molecular clouds added

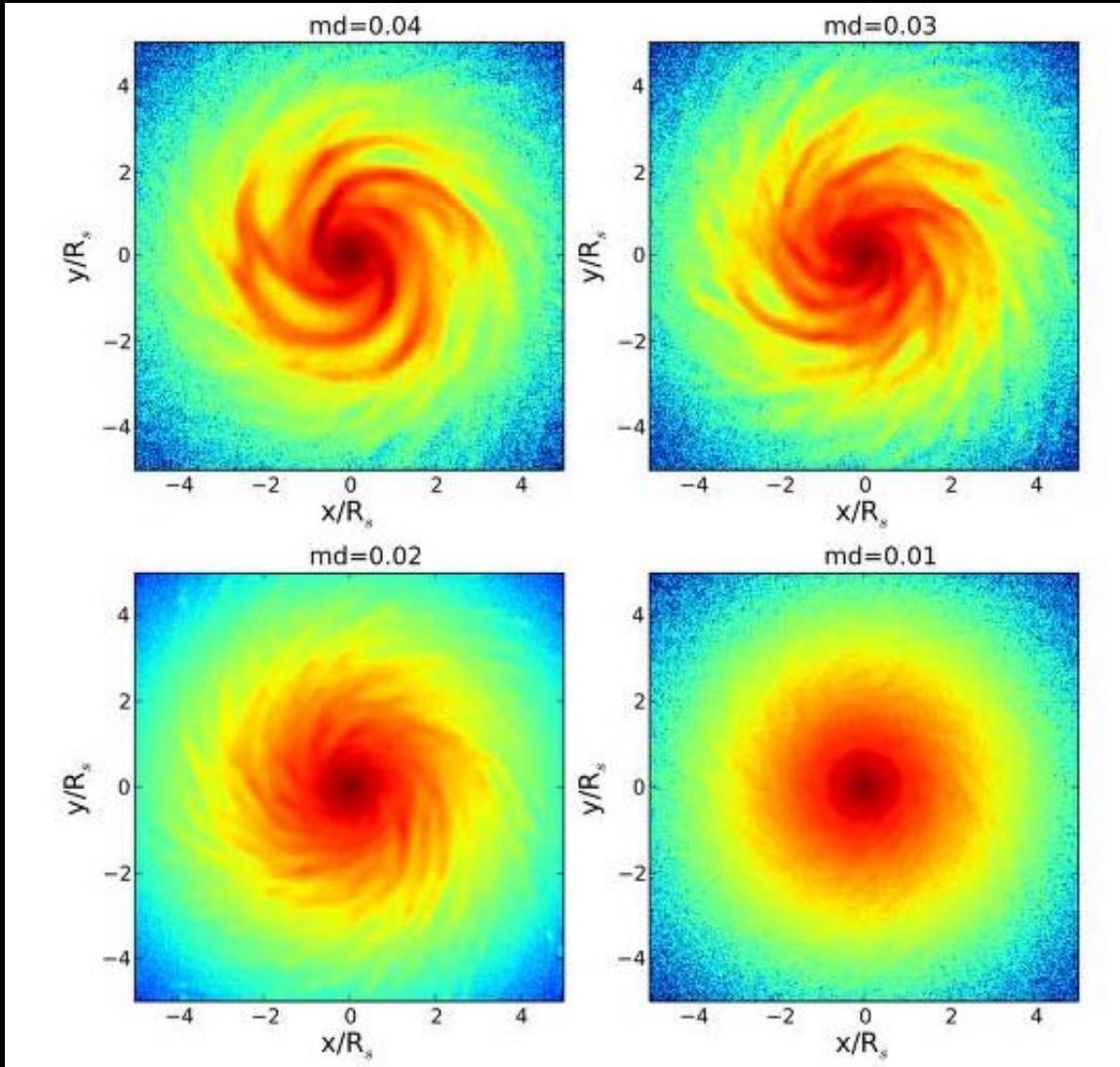
Each “*perturber*” drives a local response : a self-gravitating wakelet

Wakelets replace clouds as perturbers

Multiple wakelets amplify to *dynamically* form an arm



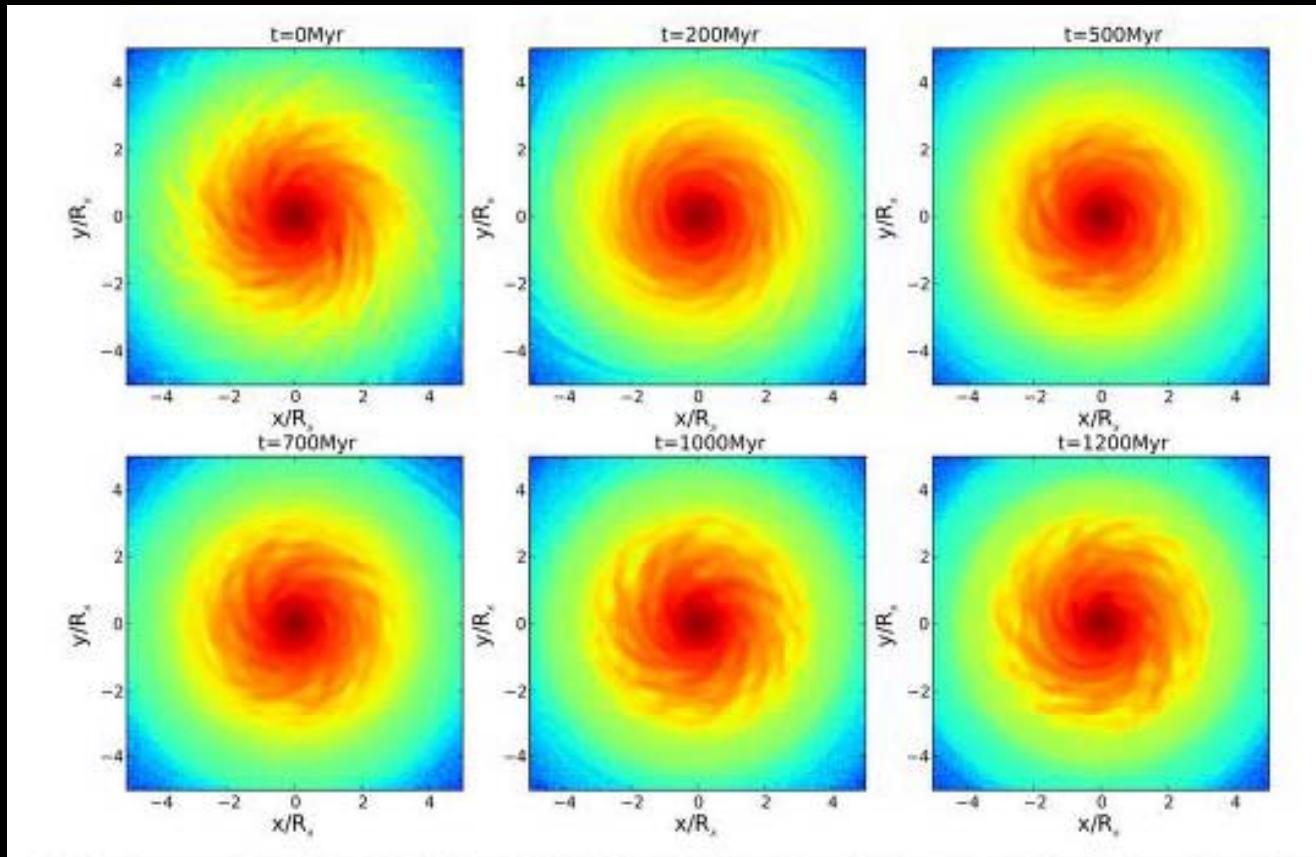
How do spirals form ... how many arms ?



Increasing the
disk/halo ratio
(*dm*) decreases
the *number* of
arms and their
amplitude



How do spirals maintain their form ?



Spiral arms are *statistically stable* when *molecular clouds* are removed

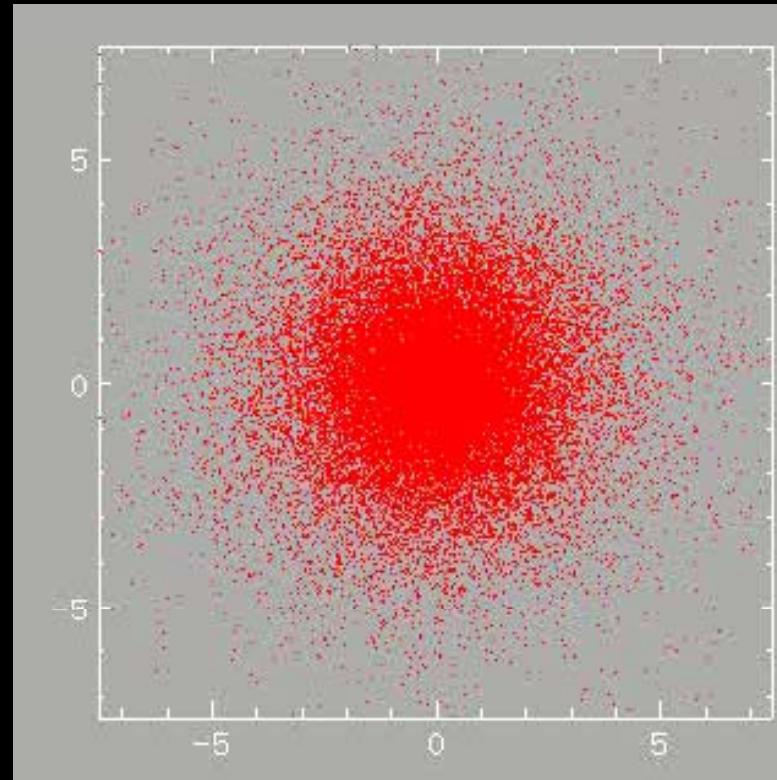
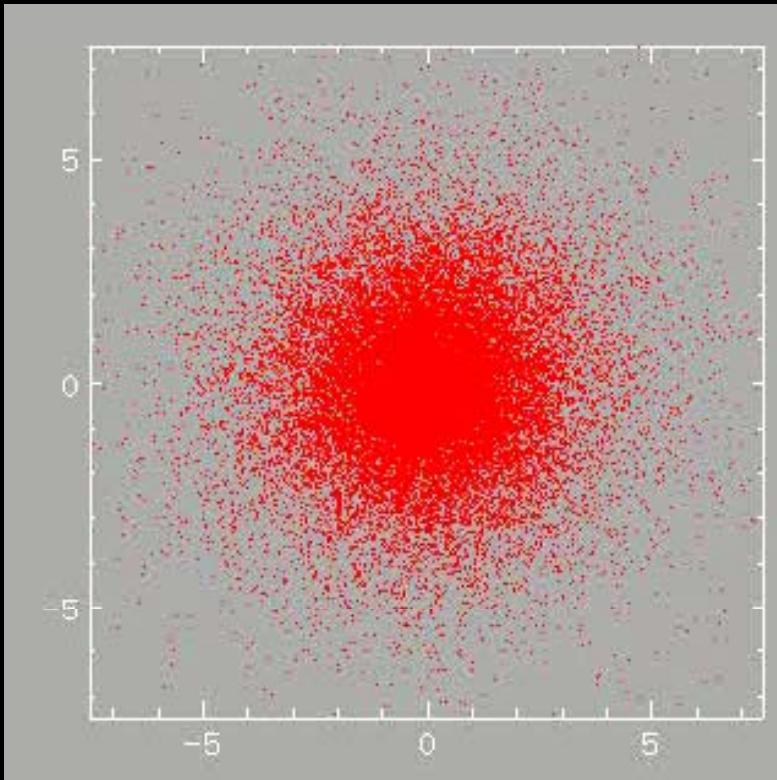


How do barred spiral galaxies form ?



High D/H

Low D/H



Rotating disks
unstable

Disk density
anomaly \Rightarrow bar
(*radial orbits*)

$f(\text{Disk}/\text{Halo})$
density ratio



How do barred spiral galaxies form ?



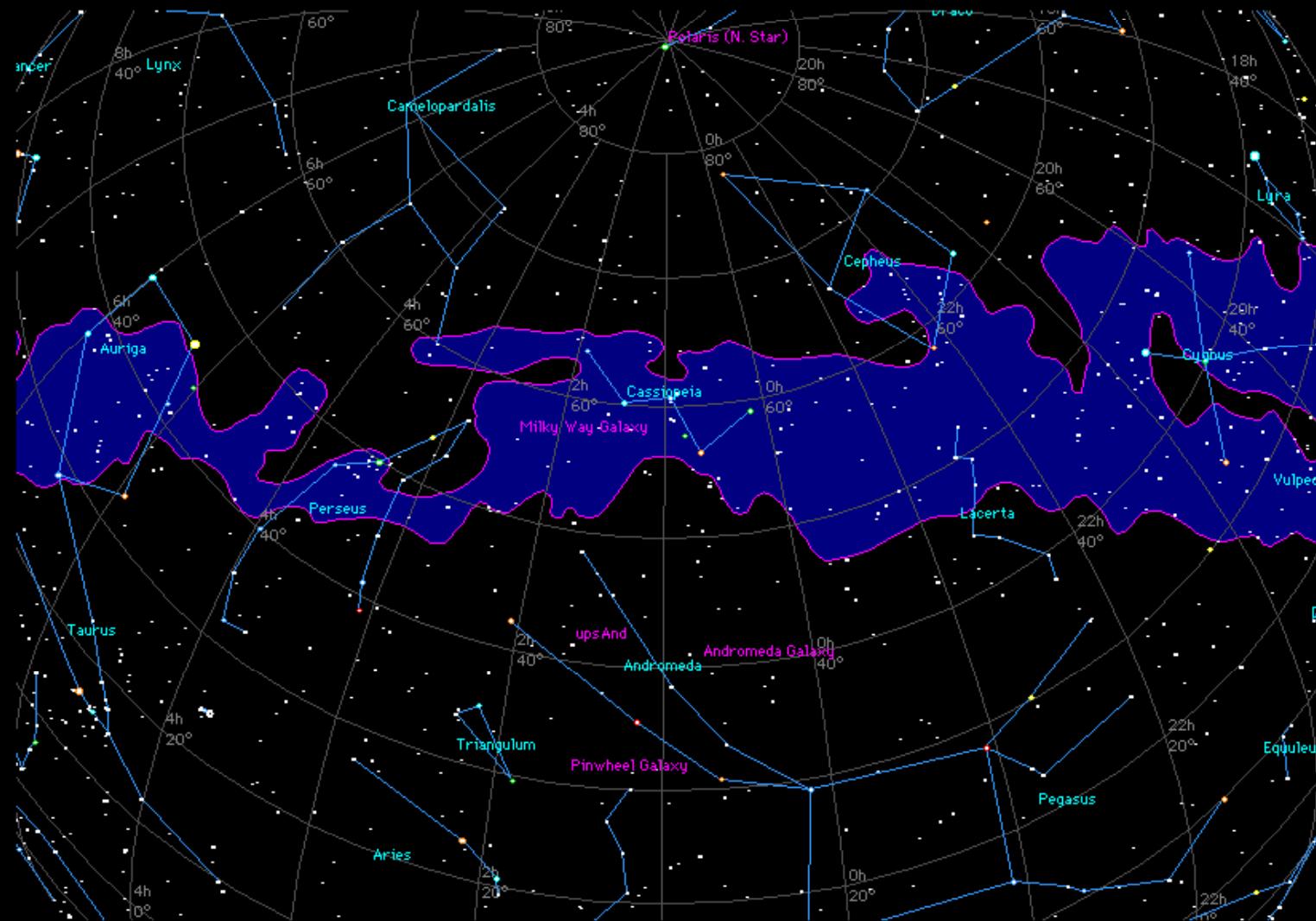
- Orbital resonance \Rightarrow channeling gas flow \Rightarrow new stars
- Radiating density wave \Rightarrow new orbits \Rightarrow bar
- Bar growth destabilises bar ...
- Oscillating evolutionary cycle (~ 2 Ga)



Milky Way... our home galaxy



Milky Way ... our home galaxy



Milky Way ... where are we, how far can we “see” ?

62/62

